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EARTH-TYPE PLANETS: MERCURY, VENUS, MARS

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INTRODUCTION

Recent years have seen tremendous progress in the study of planets of the solar system. Particularly great successes have been achieved in studies of the planets closest to the Earth -- Venus and Mars. The flights of spacecraft, together with improvement in techniques of Earth-based observations and improvements in the reliability of interpretation of data have provided for the production of new results, in many cases revolutionizing existing concepts of the nature of these planets. /1*

The Earth, Venus Mars and the planet closest to the sun, Mercury, are usually called the planets of the Earth group. This generalization is primarily based on the similar mean densities of these planets (see Table 1). This indicates that the planets of the Earth group are composed, as is the Earth, primarily of rather heavy elements, which are widespread in the solar system: Si, Fe, Ca, Al, Mg and their oxides. It has been established that the atmospheres of these planets contain gasses consisting primarily of the commonest elements H, C, O, N and their compounds and that they are oxidizing in nature, in contrast to the atmosphere of the planets of the Jupiter group. It is generally believed that the atmosphere is a portion of the volatile fraction liberated by degassing of the core during the process of differentiation of the materials of a planet into shells.

For the planets of the Earth group, localized within 1.5 a. u. from the sun, moderate differences in geometric dimensions and interesting distribution of mass are characteristic. The Earth and Venus are particularly similar in mass, while Mars and Mercury are less massive than the Earth, by approximately 10 and 20 times respectively. Of all the planets, only the Earth has /2
a satellite comparable in size to Mercury, so that from the standpoint of planetary dynamics it is actually more correct to speak of the Earth-moon system; as concerns the satellites of Mars, Phobos and Deimos, they are incomparably smaller than the planet itself.

However, the study of the planet-satellite system is significant for understanding of the problem of the long-term

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*Numbers in the margin indicate pagination in the foreign text.

evolution of an astronomical body, particularly as concerns the interaction, which is related to energy exchange.

In this review, we concentrate our attention on three planets -- Mercury, Venus and Mars. Of course, a complete presentation would require at least a brief mention of the nature of the Earth, the best studied member of the Earth group of planets, although until recently the methods used to study the Earth and its neighboring planets differed quite basically from each other. Essentially, the launching of the first artificial Earth satellite was the beginning of the modern era of investigation, allowing us to look upon the Earth as a planet and determine such important characteristics as the study of its radiation, gravitation and magnetic fields, peculiarities of its interaction with surrounding space, etc. Comparison of these results with the analogous characteristics of other planets has allowed combined analysis and a number of generalizations. In turn, the geological and geophysical methods used to study the Earth, the successes achieved in studies of its internal structure have served as the necessary basis for an understanding of the complex nature of other astronomical bodies. This combination of the traditional Earth sciences with planetary studies, until recently confined entirely to observational astronomy, has lead to the birth of a new and rapidly growing area of science -- planetary physics, the development of which will facilitate the /3
solution of basic problems related to the formation and evolution of the entire planetary system.

Unfortunately, the limited space set aside for this section did not allow us to include the Earth. The authors considered it more expedient to utilize the space for a more detailed presentation of contemporary conceptions of the other planets of the Earth group, particularly since the abundance of new information on their nature made even this task quite difficult. Naturally, the review which we present herewith has no pretentions of absolute completeness and, to a certain extent, reflects the subjective points of view and interests of the authors. The sparcity of the presentation in many cases is compensated somewhat by references to the prime sources, to which the reader interested in details can turn.

The authors consider it their duty to comment on the great labor of D. G. Rea (USA) and V. M. Vakhnin (USSR) in the preliminary preparation of data for the compositors of this review, and also to express their gratitude to all their colleagues, in close cooperation with whom the work has been done.

MERCURY

Mercury is the closest of the nine large planets to the sun; /4
in our sky, it is never further than 28° from the sun, making it quite difficult to observe Mercury from the Earth. From time to time, the planet can be seen by the naked eye as a barely noticeable bright spot among the colors of a sunrise or sunset. In the telescope, Mercury looks like a crescent or part circle, the changes in shape of which as it orbits the sun clearly show that what we are actually observing is a sphere illuminated on one side by the sun. In its closest position to the Earth (mean minimum 92 million km, minimum minimorum 80 million km), Mercury is unfortunately located right next to the sun in the sky, and turns its dark (night) hemisphere toward the Earthbound observer. This hindrance in observing Mercury from terrestrial observatories makes the already great difficulties resulting from the small angular dimensions of the object, the weakness of the energy flux arriving from it and the interference of the Earth's atmosphere, still worse. Nevertheless, researchers have succeeded in gaining priceless funds of knowledge from nature by improvement of complex apparatus and methods of observation, at the cost of difficult, at times even selfless labor. All of the (rather extensive) information now available on Mercury has been produced by terrestrial observation.

Excellent reviews have been written on Mercury (for example, [39, 51, 131, 158]). However, in recent years some of the information in these reviews has been refined. The present review includes an attempt to present the factual material on the
physics of this planet using, where possible, the very latest /5
data.

Diameter, Mass and Quantities Derived from Them

Precise knowledge of the dimensions and mass of a planet are extremely necessary for the determination of a number of parameters characterizing the physical conditions on the surface, which are important for astronautics.

The linear diameters of all planets, determined from the angular diameters measured from the Earth, are quantities derived from the numerical value of an astronomical unit of length[2]. Due to possible refinement of these values, it has been historically traditional to express the diameters of the planets not in linear measure, but rather in angular seconds at a distance of 1 a. u.

The results of measurement of the equatorial diameter of Mercury fall between 6.2 seconds and 6.9 seconds, i.e., agree with an accuracy which is far from astronomical. Reviews of the primary results can be found in [39, 87, 212]. New measurements yield the following figures. By optical methods: 6.73" ± 0.03", corresponding to a linear measure of 4882 ± 30 km [32]; according to [182], $D \geq 6.79"$, i.e., $D \geq 4920$ km. Radar studies indicate a diameter of 6.72" ± 0.008", or 4874 ± 6 km [175].

The best method for determination of the mass of any planet is to study the periods of rotation of its satellites. Since Mercury has no satellites, its mass is calculated by the difficult method of observing the effects of its gravitational interactions with other astronomical bodies.

The results of various authors [105, 129, 175], produced to three or four significant digits, agree with an accuracy only extending to the second decimal point. We will be forced to limit ourselves to this accuracy in our review. The mass of Mercury in units of the ratio of the mass of the sun to the mass /6
of the planet is near $(6.0 \cdot 10^6)^{-1}$.

Estimates of the mass and diameter of the planet can be used to determine quite easily the acceleration of the force of gravity and the parabolic (escape) velocity at the level of the surface; the former amounts to about 38% of its value on the Earth, the latter to about 4.3 km$\cdot$sec^{-1}.

Depending on the values of the mass and diameter, a mean density of 5.30 to 5.46 is calculated [181]. The high mean density of Mercury (in comparison to the density of substances in the Earth at the level of the corresponding pressure) is explained by an abundance of the heavy elements. The chemical composition of Mercury is apparently dominated by iron [21, 65, 180]. The conclusion of the high content of iron and, consequently, the limited content of silicates, indicates a significantly lower content of radioactive substances in Mercury than in the substance of chondrite meteorites. However, we know that the decomposition of the radioactive elements contained in the silicates is one factor in the internal heating of the planets. Calculations [31] of the thermal history of Mercury have shown that in all stages of its evolution, the temperature deep in the planet has never reached the value necessary to melt silicate substances or iron. This indicates that substances in Mercury should not be segregated according to specific gravity, with iron in the central core.

Various models of the internal structure of Mercury have been described in [135], where models with homogeneous distribution of metallic iron and with iron segregated in the core were both studied.

The Surface: Photometric Properties and Modern Data on Relief

The surface of Mercury appears bright in sunlight, but measurements have shown that it is rather dark, rather more precisely dark brown. The visual Bond albedo[3] for Mercury is 0.056 [111], the integral albedo is 0.09 [38]. The mean brightness of the surface of Mercury increases sharply as the phase angle approaches 0. Curves of the variation of brightness as a function of phase angle for Mercury and the moon practically correspond [106, 111]. The spectral reflectivity increases with increasing wavelength, at least up to 1.6 μ [38]. The results of measurement of spectral reflectivity of Mercury, adjusted to 0 phase, within the limits of 0.32 to 1.05 μ, are shown in Figure 1, which was borrowed from [143]. The curve of the reflectivity of Mercury is similar to the curve for mountainous and maria areas of the surface of the moon, and differs from the curve form the floors of lunar craters. Based on these results, MacCord and Adams concluded that the surface of Mercury is probably covered with moonlike solid matter, rich in dark volcanic glass such as pyroxene. The reason for the low albedo may be the high content of iron and titanium in the minerals [143]. /7

Under exceptionally favorable conditions, which occur rather rarely, light and dark spots can be seen on the surface of Mercury through a telescope.

Attempts have been made repeatedly to make a map of Mercury. We will not study historical maps here, since their compositors used false data on the period of axial rotation of the planet. New attempts to draw maps of Mercury on the basis of modern concepts have been undertaken by Camichel and Dollfus [67, 68] and by Cruikshank and Chapman [77]. The most modern, best map of the details of the surface of Mercury, showing the coordinates of details drawn, was composed in 1972 by Murray, Smith and Dollfus /8 on the basis of materials from photographic and visual observations in 1942-1970 in the astronomical observatories of Pic-du-Midi (France) and New Mexico (USA).

The new map is shown in Figure 2. The longitudes are given in the new system, recommended at the Fourteenth Session of the International Astronomical Union (Brighton, 1970) [162]. The compositors of the map concluded that the visible contrast of details on the surface of Mercury is somewhat less than the contrast between Maria and continental areas on the moon. Possibly, the decrease in contrast results from erosion of images of dark details during observations of Mercury, since the angular resolution produced is 300 times poorer than that of observations of the moon. The area between 350° and 90° hermographic[4] longitude, occupying over one fourth of the surface of the planet, shows practically no large contrast details.

The authors of [162] note that the details on the surface of Mercury remained unchanged throughout the more than 30 year period of observations used, and that no atmospheric haze was observed in any area of the planet.

Studies of the surface relief of Mercury are beyond the capabilities of optical methods of Earth-based astronomy. During the past decade, radar has been successfully used in studies of the surface of the closest planets. The capabilities of radar have increased both due to improvements in apparatus, and due to the use of new methods of data analysis. However, Mercury is a very difficult object for investigation, since a radio echo signal returning from Mercury has approximately 1/100 the power of a signal returning from Venus.

Prior to 1970, a group of researchers at MIT unsuccessfully attempted to use two-dimensional radar spectra (delay time and frequency) to estimate the profile of the surface of Mercury [204]. The weakness of the reflected signal prevented differentiation of significant relief details or determination of the inclination of the surface of Mercury from the surface of a sphere. Two more successful radar studies of Mercury were conducted in 1970-1971 at Goldstone by the California Institute of Technology at a wavelength of 12.5 cm, and at Haystack by MIT at a wavelength of 3.8 cm. Sufficient sensitivity was achieved to study the scattering characteristics. Both the scattering function and the polarization of radiation at 12.5 cm wavelength showed that the surface of Mercury is significantly rougher than that of Venus, as concerns small irregularities [101]. Measurements at 3.8 cm [116] in several areas of the equatorial portion of the planet showed that the mean slope was approximately 10°. This value changes significantly with longitude, but the variations are less than in the cases of Venus and Mars. Topographical details were observed with variations in surface level of the planet on the order of 1-3 km. These are significantly less than the variations in altitude (or more precisely, in planetary radius) observed on Mars. /9

Radar studies have measured the "reflection factor" of the planet in the microwave band. The scattering cross section[5] of Mercury varied during observations within limits of 4 to 8% from the optical cross section, i.e., was approximately the same as that of the moon.

Parameters of Axial (Diurnal) Rotation of the Planet

Attempts were made repeatedly to find the period of axial rotation of the planet by observation of spots on the surface. However, the old visual observations led to the false conclusion that Mercury always turns the same hemisphere toward the sun, /10 i.e., to the conclusion that the sidereal period of axial rotation was equal to the sidereal[6] period of orbital rotation (87.97 days). This false opinion was held right up to the discoveries of Pettengill and Dyce [167]. They found, by radar studies, that the sidereal period of axial rotation of Mercury is 59 ± 3 days. This value was subsequently refined. Thus, actually, Mercury does rotate, but so slowly that its axial rotation is difficult to observe during the short interval of time favorable for visual observations. Many authors explain the long life of the erroneous hypothesis of synchronous rotation of the planet as the result of the "fatal" quasicomparability of the period of this rotation with the period of recurrence of conditions most favorable for observations of Mercury (in one astronomical observatory outside the tropical belt -- with this refinement, the statement is correct). The necessary combination of factors repeats itself every 3 synodic periods, i.e., every 348 days, during which time Mercury turns by approximately a whole number of rotations both in relationship to the sun and in relationship to the Earth. In this case, the apparent displacement of details on the planetary disc and the position of the subsolar point among them recur with hardly noticeable changes.

Incidently, it has been optical observations which have helped to refine the period of rotation of Mercury after its rough but reliable estimation by the radar method. Kamishel' and Dollfus [67] determined a period of 58.67 ± 0.03 days on the basis of processing of the archives of the Pic-du-Midi Observatory for 1942-1966. Smith and Reese also used photographic archives built up over many years and produced a period of rotation of 58.663 ± 0.021 days [202]. The accuracy of the radar observations has been continually improved and now approximates the accuracy of optical methods. New radar observations [101] indicate a period of 58.65 days, with an error of not over 0.4%. /11

Murray, Smith and Dollfus supplemented the earlier archives of photographs and drawings of Mercury with new optical observations made at the Pic-du-Midi and New Mexico Observatories and determined a rotation period of 58.644 ± 0.009 days [162]. The direction of the axis of rotation of the planet has been found to be perpendicular to the plane of its orbit with a probable deviation of not over 3°.

The period of axial rotation of Mercury is not a random figure: a time interval of 58.6462 days is precisely 2/3 of the orbital period of Mercury. This is an interesting version of resonance in spin oscillations, caused by the effects of the gravity of the sun on the planet, within which the placement of mass cannot be considered strictly concentric. A rotation with a period of 2/3 the period of orbital rotation should be stable [71]: the small axis of the ellipsoid of inertia of the planet is oriented toward the sun each time Mercury returns to its perihelion. It is demonstrated in [99] that development of a 3/2 spin-orbital resonance requires a compression of the ellipsoid of inertia in the equatorial plane $(B - A)/C \gtrsim 10^{-5}$, i.e., very slight.

The Problem of the Atmosphere of Mercury

A. Dollfus [85, 86] found an atmospheric pressure at the surface of Mercury of approximately 1 millibar, based on measurements of the polarization of the light scattered by the planet in various areas of the spectrum. Moroz [38] produced an estimate of the same order of magnitude (CO_2 content equal to 0.3-7.0 g/cm^2) on the basis of the excess absorption in the CO_2 band about 1.6 μ in the spectrum of Mercury over that of the Earth. However, an attempt of Binder and Cruikshank [62] to repeat the measurements of Moroz was unsuccessful. As concerns the pecul- /12 iarities of polarization of Mercury, O'Leary and Rea [164] explain them on the basis of surface properties alone, without the participation of atmospheric effects.

The work of Belton et al. [59] on measurements in the 1.05 μ band determined an upper limit for the content of CO_2 on Mercury of 5 m·atm (partial pressure at the surface less than 0.35 mb); while Bergstral et al., on the basis of observations of the band around 1.20 μ [61], evaluated this upper limit as not over 0.58 m·atm (partial pressure approximately 0.04 mb). These data place the results indicating detection of CO_2 on Mercury in doubt.

In order for gas molecules not to dissipate from Mercury, they would have to be, first of all, rather heavy and, secondly, resistant to dissociation under the influence of sunlight. This criterion is satisfied by Ar^{40}, widely distributed in the solar system. Observations do not exclude an argon atmosphere with a pressure at the surface of Mercury of 1 mb or less, but its existence is only a hypothesis.

The similarity of the photometric properties of the surface of Mercury and of the moon can serve as an argument (though not a very convincing one) in favor of the assumption that the surface of Mercury has been subjected to the influence of the solar wind. Based on this, Sagan [186] and O'Leary and Rea [164] have produced estimates of the upper limit of atmospheric pressure at the surface of the planet as approximately 10^{-5} mb. Belton, Hunten and McElroy [59], based on calculations of the rate of dissipation, produced an upper limit at around 10^{-6} mb. Banks et al. [53], discussing various possible models of the atmosphere of Mercury, allow for the possibility of existence of an exospheric model consisting of He^4, Ne^{20} and Ar^{40}, with a summary upper limit of $2 \cdot 10^{14}$ particles in a unit column. The /13 structure of the model is determined by the solar wind.

Conditions of Insolation and Surface Temperature

Determined by the combined effects of axial and orbital rotation, the length of one solar day on Mercury is exactly equal to 3 stellar days or 2 Mercurian years, at 176 Earth days, i.e., mean solar Earth days. Approximately half of this time is spent in daylight. The sun has variable size in the Mercurian sky, and moves from east to west unevenly, due to the eccentricity of the orbit and the periodic changes in heliocentric angular velocity of the planet. Twice each solar day (namely at each perihelion), the sun increases in size and stops, after which its motion reverses for some hundred hours, after which the sun stops once more, then takes up its course toward the west.

The quantity of solar energy received per unit time and unit area perpendicular to the rays of the sun (the so-called solar constant, equal to $2.00 \pm 0.04\ \mathrm{cal \cdot cm^{-2} \cdot min^{-1}}$ at the upper boundary of the Earth's atmosphere) on Mercury at the perihelion is approximately double the value at the aphelion, and is ten times greater than on the Earth, i.e., reaches $14\ \mathrm{kw \cdot m^{-2}}$. The daily cycle of illumination is not the same at different hermographic[4] longitudes on the equator. Around longitudes 0° and 180°, the sun has its maximum angular size at the upper culmination and moves very slowly in the sky, whereas around longitudes 90 and 270°, it has its minimum angular dimensions at noon and crosses the sky relatively rapidly, delaying only at the horizon.

The daily heating of the surface, obviously, decreases with increasing latitude, right up to the poles of rotation. It is interesting to note that at the poles one might observe conditions of continuous or near continuous illumination: the sun moves along the mathematical horizon with a period of 176 days; the center of the sun dips below the horizon every 38 days by a quantity equal to the inclination of the equator of the planet to its orbit (an inclination less than, perhaps much less than 3°); the upper edge of the sun, if it does disappear, disappears only briefly, since the depth of immersion of the center beneath the line of the mathematical horizon is approximately equal to the radius of the sun as seen from Mercury. /14

The great length of day and night on Mercury produce great differences between the temperature of the noon and midnight sections of the surface, while the closeness of the planet to the sun and its low albedo produce great heating of the surface during the day.

The temperature on Mercury has been determined on the basis of changes in the natural thermal radiation of the planet in the portion of the IR range where the contribution of reflected solar radiation is negligible.

At the mean distance from the sun, the brightness temperature[7] of the surface at the subsolar point of Mercury corresponds to the Planck radiation of an absolutely black body at a temperature $T_b = 613°$ K [169]. The color temperature[7] (according to the ratio of intensities at $\lambda = 2.2$ and $3.4\ \mu$) at the perihelion has been found to be $T_c = 670° \pm 20°$ K [39].

Infrared thermometry of the dark side of Mercury involves greater technical difficulties, since it requires, in addition to high angular resolution of the apparatus and ideal atmospheric /15
conditions, reliable protection of the apparatus from the radiation of the crescent of the bright hemisphere of the planet and extremely high sensitivity of the detector. Nevertheless, measurements of such world record difficulty have been successfully performed. Murdock and Ney [161], studying the 3.75-12.0 μ range, found a nighttime surface temperature of $111 \pm 3°$ K. Thus, the amplitude of diurnal fluctuations in temperature on Mercury is over 500° K.

Modern observations of the thermal radiation of Mercury have not been limited to the IR band. Radioastronomy measurements have also been performed in the microwave band allowing the thermal mode of the subsurface layer of the planet to be determined at various depths, and the physical properties of the outer cover of the planet to be determined. The greater the wavelength of the radiation used, the greater the depth responsible for its origin. The depth of penetration of electromagnetic oscillations (i.e., the depth of the radio radiating layer) $\ell_e = 1/\kappa$ where $\kappa(\lambda)$ is the electromagnetic wave absorption factor, λ is the wavelength. Equally important for us is another expression of the same quantity: $\ell_e = \delta\ell_t$, where δ is a coefficient which depends on the properties of the material, ℓ_t is the depth of penetration of the temperature wave, defined by a decrease in amplitude of fluctuations of temperature by e times in comparison to the value on the surface. At a depth three to four times ℓ_t, the fluctuations in temperature are practically nil. This determines the thickness of the layer of rock heated by the sun during the course of the day. The theory of this problem has been presented in detail in [23].

The temperature measured in the microwave band depends on the relationship between the thickness of the layer heated by the sun and the thickness of the radio radiating layer.

Reviews of results of radiometric observations of Mercury at wavelengths of 0.19 cm to 11.3 cm can be found in [100, 102, 158]. The numerical values of the heat-physical parameters of Mercury are presented at the end of this section. /16

The heat-physical behavior of the outer cover of the planet indicates its exceptionally low heat conductivity. The amplitude of diurnal fluctuations in temperature at a certain depth, as would be expected, is considerably less than that indicated by measurements in the IR band. The data from microwave radio-astronomical observations indicate that the brightness temperature, averaged over the entire visible disc of Mercury, varies both with phase angle i and with longitude L of the center of the disc, and also depends on the ratio δ of the depth of penetration of the electrical and thermal waves. The most complete results of observations, processed by the method of least squares, are as follows:

$$\lambda = 0.33\text{ cm};\; T_1{}^\circ K = \underset{\pm 7}{296} + \underset{\pm 9}{127}\cos(i + \underset{\pm 4^\circ}{16^\circ}) +$$

$$+ \underset{\pm 9}{16}\cos(2L + \underset{\pm 28^\circ}{16^\circ});\; \delta/\lambda = 1.0\text{ cm}^{-1}\text{ [92]};$$

$$\lambda = 3.75\text{ cm};\; T_2{}^\circ K = \underset{\pm 4}{380} + \underset{\pm 3}{55}\cos(i + \underset{\pm 4^\circ}{32}) +$$

$$+ \underset{\pm 3}{11}\cos(2L - \underset{\pm 11^\circ}{8^\circ});\; \delta/\lambda = 1.3\text{ cm}^{-1}\text{ [126]};$$

where λ is the electromagnetic radiation wavelength,
i is the sun-planet-Earth angle,
L is the hermographic longitude in the system of longitudes described in [77]. The position of the zero meridian in this system differs from its position in the International Astronomical Union system of 1970.

The great differences between the expressions of temperature in the millimeter and centimeter wave bands unfortunately cannot be explained by the difference in effective depth of the radiating layer alone. Concerning the application of the theory of radio radiation developed for the moon to Mercury, Gary indicated that it is necessary to consider the temperature dependence of heat-physical parameters in this case [96]. /17

Morrison [157, 158] has calculated the average brightness temperature of Mercury in various bands of thermal radiation as a function of phase angle and position in its orbit, considering the dependence of heat conductivity on temperature. Comparison of the results of these calculations with the most reliable observation results allowed Morrison to select the most probable values of parameters characterizing the thermal and electrical properties of the subsurface layer of Mercury. Some of these parameters are presented below:

Density $\rho = 1.5 \pm 0.4\ g \cdot cm^{-3}$;

Thermal inertia $\gamma = (k\rho c)^{1/2} = (15 \pm 6) \cdot 10^{-6}\ cal \cdot cm^{-2} \cdot sec^{-1/2} \cdot {}^\circ K^{-1}$;

Parameter $\delta/\lambda = 0.9\ cm^{-1} \pm 0.3\ cm^{-1}$, where δ is the ratio of the depth of penetration of the thermal and electrical waves, λ is the wavelength of electromagnetic radiation in centimeters;

Heat conductivity factor $k = (4 \pm 2) \cdot 10^{2}\ cal \cdot cm^{-1} \cdot sec^{-1} \cdot {}^\circ K^{-1}$;

Depth of penetration of thermal wave $\ell_t = 11\ cm \pm 6\ cm$;

Dielectric constant $\varepsilon = 2.9 \pm 0.5$;

Loss angle tangent $\tan \Delta = 10^{-2}$.

The similarity of the characteristics of Mercury and the /18
moon indicates that there are no sharp differences in the mineral composition and structure of the outer layers of these two bodies.

These are the basic contemporary concepts of the nature of Mercury. Further growth in the level of our knowledge in this area of science can be significantly accelerated apparently only by means of spacecraft.

VENUS

Venus is the inner planet closest to the Earth and the brightest light in the sky after the sun and the moon, and for many centuries has been a subject of constant attention of astronomers. Right up to the mid 1950's, it was considered possible that well developed forms of life might exist on Venus. Although this attractive idea has been abandoned at present, interest in the planet has not decreased, but more probably has increased, since Venus has been found to be a very special and surprising world in terms of its natural conditions, full of riddles and surprising facts. /19

The tremendous capabilities of automatic spacecraft have probably been best shown in our study of Venus. For several years, a planned program of studies of Venus has been conducted in the Soviet Union. The flights of the Venera 4, 5, 6, 7 and 8 automatic spacecraft have allowed us to conduct a broad range of studies. The results of these experiments, together with data produced by the American Mariner 5 flyby, are of fundamental scientific significance and have served as the basis for our current conceptions of Venus [151].

Basic Astronomical Characteristics

Venus moves in a near circular orbit within that of the Earth at a distance of some 108.1 million killometers from the sun, or 0.723 a. u. The velocity of the orbital motion of the planet is approximately 5 km/sec greater than the orbital velocity of the Earth, at 34.99 km/sec. The time required for one rotation of the planet around the sun (the sidereal period) is 224.7 Earth days. The synodic period (time between two successive identical conjunctions, or two phases of Venus) averages 584 days. The phases of Venus are similar to phases of the moon. The planet is located at its minimum distance from the Earth (about 40 million km) in the lower conjunction, in the position between the Earth and the sun (at phase angle $\alpha = 180°$), at which time it turns its dark side to us. Near the upper conjunction, when the planet is located beyond the sun ($\alpha = 0$) we observe its almost fully lighted disc. The intermediate positions ($0 < \alpha < 180°$) corresponds to intermediate phases of partial illumination of Venus for the terrestrial observer, from a narrow crescent to a nearly full disc. The visible angular diameter of the planet varies between the upper and lower conjunctions by almost 6.5 times, from 9.9 seconds to 64.0 seconds. /20

Venus is brightest (stellar magnitude about 4.3) at its maximum angular distance from the sun, reaching up to 48° under the most favorable conditions, in the position of the so-called "pauses." The angular diameter of the disc at these moments is about 40 seconds. The period of the beginning of visibility of the planet at twilight corresponds to passage of the upper conjunction, after which its angular distance from the sun first increases, then decreases; at the same time, the visible diameter of the disc increases, while its illuminated portion decreases. The ascent of Venus in the east in the morning is accompanied by the passage of the lower conjunction, after which the visible diameter of the disc begins to decrease, while its illuminated /21 portion increases. The difference in the rising and setting of Venus and the sun reaches almost 4 hours. Due to this peculiarity of the visibility of Venus it has long been called the morning or evening "star."

Observations of Venus in its lower conjunction indicate that the plane of its orbit is inclined to the ecliptic at angle $i = 3° 23' 39''$. Therefore, the disc of the planet during the periods of conjunctions is usually not projected on the disc of the sun. The transit of Venus across the disc of the sun occurs only when at the moment of a lower conjunction, both planets are located on the line of intersection of their orbits. These events, schematically illustrated on Figure 3, occur comparatively rarely, periodically repeating at intervals of 8 and slightly over 100 years (see [15]). Observation of the transit of Venus across the disc of the sun of 6 July 1761 allowed the Russian scientist M. V. Lomonosov [27] to make the fundamental discovery of the presence of an atmosphere with the planet.

Venus is the closest to the Earth of all the planets of the solar system as to its dimensions, mass and mean density. Its radius is 0.948 Earth radii ($R_♀ = 6050 \pm 0.5$ km [69]). The ratio of the mass of the planet to the mass of the Earth is about 0.81, while its mean density is 4.86 $g \cdot cm^{-3}$ as compared to 5.5a $g \cdot cm^{-3}$ for the Earth. Based on measurements of the orbit of the Mariner 5 spacecraft, the mass of Venus is 408,522 ± 3 times less than the mass of the sun. The primary parameters characterizing the elements of the orbit of Venus, its geometry, mass and related quantities are presented in Tables 1 and 2 at the end of the chapter, where for comparison we also show the /22 corresponding parameters of the Earth [47].

For a long time, the question of the elements of the rotation of Venus about its axis and the ecliptical coordinates of its poles, i.e., the tilt of the axis of rotation in relation to the plane of its orbit around the sun, were the subject of animated debate. Many visual and photographic, and later spectral observations in the visible, infrared and ultraviolet areas of the spectrum were made in attempts to follow the visible movement of characteristic details (individual spots and bands) across the disc of the planet. However, the peculiarities observed, parts of the cloud layer which constantly covers the planet, were generally unstable and the subjectivity of the observer has a strong influence on any conclusions concerning periodicity of repetition. Values of a few days to a few months were reported, with most observers assuming synchronous rotation of the planet.

Significant progress was made in the study of the nature of the rotation of Venus as a result of radar studies begun in 1958. These measurements [24, 44] gave an impression of very slow rotation of Venus in the reverse direction, i.e., clockwise when observed from the north pole of the world, in contrast to the other planets of the solar system. One full rotation occurs in 243.0 Earth days. The combination of the annual motion and the reverse diurnal rotation of the planet means that one Venusian year includes two days, each lasting 116.8 Earth days. This means that during a Venusian year, the sun rises and sets /23
twice. An observer on the surface of Venus would be surprised to see the sun rise in the west and set in the east, and would find himself under conditions similar to the "polar night" and "polar day", lasting some two Earth months, both in the equatorial and the moderate latitudes. The measured coordinates of the rotation vector (direct ascension α and inclination δ) lead to the conclusion that the axis of rotation of Venus is almost perpendicular to the plane of its orbit: the angle between the plane of the equator and the plane of the orbit is less than 3°. This means that there are practically no seasonal changes in the annual rotation of the planet.

Figure, Topography, Surface

Unfortunately, information on the nature of the solid body of Venus is quite limited. The results of measurements with the radio telescope of the Lincoln Laboratory of MIT at Haystack performed in 1968-1969 at a wavelength λ = 3.8 cm [115, 204], have shown that in the equatorial plane the cross section of the planet is approximated by an ellipse, the difference of the half axes of which amounts to 1.1 ± 0.25 km. The long axis of the ellipse forms an angle of 55° (clockwise) with the direction to the Earth in the lower conjunction. The center of mass is displaced relative to the center of the figure of the planet by 1.5 ± 0.25 km.

From the point of view of topography and physical proper- /24
ties, there is great interest in the results of mapping of the reflective properties of the surface of Venus in the radio band. These experiments [115] have indicated local areas of increased reflectivity extending for hundreds and thousands of kilometers. The map of the reflective properties of the surface, limited by longitudes 0 and -80° and latitudes of -50 to +40°, is shown in

Figure 4. The most characteristic areas are α and β. Large circular formations like the lunar maria (shaded) have also been found, as well as individual specific details within them, marked with Roman numerals. The nature of the areas of increased reflection can be explained, in addition to the obvious assumption of more uneven surface and the presence of elevations leading to a decrease in the effective absorptive layer of the atmosphere, also by differences in surface material and, consequently, in dielectric permeability ε. The mean value of ε, concluded from radar measurements, falls within limits of 4-4.5.

Radar studies have detected altitude differences of 3-5 km on the surface of Venus. The region of greatest elevation is at a longitude of abour 31° (according to the Ingalls-Evans system [115], according to which the meridian passing through the α area is taken as the zero meridian). It is possible that relief differences of the planet's surface may be expressed still more sharply. However, data on polarization of radio waves reflected by the planet show that the polarization of most /25 energy of these waves corresponds to mirror reflection, and that the ratio of depolarized reflection to polarized reflection for Venus is significantly less than for the moon. This indicates that the microstructure of the surface of Venus is, on the average, smoother than that of the moon.

In general, the available experimental data from radar probing indicate significant variability of the physical properties of the surface of Venus and, apparently, a rather complex topography.

The flight of Venera 7 yielded the first estimates of the physical and mechanical properties of the surface of Venus. A qualitative analysis of the landing conditions of the spacecraft was made on the basis of data on the changes in power of the signal received on the Earth at the moment of contact with the surface. The vertical velocity of the spacecraft was damped in a time of less than 0.2 sec, most probably corresponding to hard soil. Had the vehicle struck a low-viscosity fluid or a thick dust layer, the process of deceleration of the spacecraft and the drop in signal level would have been significantly slower. Considering data on the strength of the spacecraft, we can make an upper estimate of the soil strength $P_s \leq 80$ kg/cm^2. On Earth, this level of soil strength corresponds to rocks such as volcanic tuffs. However, comparison of the nature of change of the signal power at the moment of touchdown of Venera 7 with results of tests involving impacting of a descending vehicle against various /26 soils gives reason to believe that the soil strength is significantly lower than this upper limit, not over 2 kg/cm^2 [34].

During the flight of Venera 8, changes in the power of radio waves reflected by the surface of the planet as the spacecraft descended were used to estimate the dielectric permeability, which differs significantly (by a factor of about 1.5) from that indicated by radar data. This means that the surface layer of the planet in the region of the descent of Venera 8 is rather loose and, most probably, consists of crushed rock. Its density is about 1.5 g/cm^3 [6].

The results of analysis of the nature of the Venusian surface rock performed by A. P. Vinogradov et al. [10] by means of the gamma spectrometer installed on Venera 8 are of tremendous significance for our understanding of the geology of Venus. Preliminary study of the spectrum and the summary intensity of gamma radiation created by the natural radioactive elements contained in the surface layer (U, Th, K) indicates that the material of the Venusian surface in the area where the spacecraft landed contained 4% K, 0.0002% U and 0.00065% Th. The content of these elements and their ratio indicate that the material of the surface is similar in composition to the granites common on Earth.

The Atmosphere of Venus /27

The dense, almost uninterrupted cloud layer of Venus prevents us from observing its surface in the visible area of the spectrum. However, observations in the visible and particularly the infrared range, which have become possible due to successes in infrared spectrophotometry, have yielded some information on the atmosphere of this planet. The presence in the Venusian atmosphere of such gasses as CO_2, H_2O, CO, HF, HCl has been recorded. The upper limits of the content of possible impurities has been estimated, and estimates of the temperature and pressure near the cloud boundary visible from the Earth have been made [39]. However, these measurements, even with the resolution of 0.1 A achieved in the near infrared area of the spectrum, have indicated only the relative contents of individual gasses, and have not answered the question of the primary composition of the Venusian atmosphere.

The determination of the absolute concentrations of components and the possibility of extrapolation of values of temperature and pressure at the tops of the clouds into the atmosphere beneath the clouds is hindered by the uncertainty of the optical properties of the cloud layer.

The clouds significantly influence estimates of the effective depth of formation of the absorption lines and the processes of radiation transfer, while the various possible characteristics of scattering, the spectrum of particle dimensions and their nature allow the parameters of reflection from the cloud layer to vary over a broad range; at the same time, the cloud boundary itself is not sharp. As a result, estimates of the parameters /28 of the atmosphere at the level of the clouds depend on the selection of an idealized model. Naturally, optical measurements cannot answer questions on the properties of the atmosphere beneath the clouds or the temperature and pressure at the surface of the planet.

Radio astronomy measurements, which have been developed intensively since the late 1950's, unexpectedly determined a surprisingly high radio brightness temperature for Venus -- about 600-650° K [24].

It was found to be several times higher than the radio brightness temperatures of the Earth and Mars, which correspond approximately to the mean surface temperatures of these planets. The first natural explanation of this result was the assumption that the surface of Venus, which radiates intensively at centimeter wavelengths, for which the atmosphere is almost transparent, was actually heated to this temperature. In this case, however, such attractive and popular hypotheses as the existence of oceans and luxurious vegetation on the planet would have to be abandoned, which was difficult even from the purely psychological standpoint.

Attempts have been made to make the results agree with the idea of a moderate climate on Venus. Hypotheses have been set /29 forth of a superdense ionosphere, of glowing electrical discharges in the atmosphere, of generation of radiation by movement of electrons in a magnetic field and other mechanism, each of which could be a source of nonthermal radio radiation or a hot atmosphere, explaining the observed microwave spectrum of Venus. Upon further analysis, these mechanisms have all been found inadequate to explain the available experimental data. Nevertheless, the question of the source of the high radio brightness temperature and, consequently, of the temperature of the atmosphere and surface of Venus remained unanswered.

Still greater uncertainty existed in estimates of the pressure at the surface of the planet. With the known chemical composition of the atmosphere, even under the assumption that the surface of Venus was hot, values from a few atmosphere to several hundreds of atmospheres were proposed. There was no information on the nature of the change of temperature below the clouds, on the depth of the atmosphere. Spacecraft were called upon to answer these questions of principle.

One of the most important results of the flight of the Venera spacecraft was direct determination of the chemical composition of the atmosphere [9]. The Venera 4, 5 and 6 spacecraft were equipped with simple gas analyzers for determination of the chemical composition of the atmosphere. Amplitude and threshold methods were used to estimate the content of carbon /30 dioxide, nitrogen, oxygen and water vapor. A coloristic method was used by Venera 8 to determine the ammonia content [6]. The measurements were performed at several levels at pressures of 0.6, 2 and 10 atm. In contrast to the earlier conceptions of the predominant content of nitrogen, it was found that the atmosphere of Venus consists almost entirely (93-100%) of carbon dioxide, while the volumetric content of nitrogen (if it is present at all) is not over 2%. The Venusian atmosphere contains less than 0.1% oxygen, water vapor near the cloud layer amounts to not over 0.1-1.0%, and the ammonia content is 0.01-0.1%.

Terrestrial spectroscopy indicates lower upper limits for the content of oxygen, water vapor and ammonia (10^{-3}, 10^{-2} and 10^{-5}% respectively). As concerns O_2, this result agrees with the threshold estimate of the gas analyzers. As concerns H_2O and NH_3, we must consider the different levels of the atmosphere to which the direct and spectroscopic measurements relate, and the possibility of "precipitation" of water vapor and ammonium salts due to condensation. Probably, the upper spectroscopic estimates are correct for the atmosphere above the cloud layer. the maximum estimate is yielded by analysis of the microwave spectrum of Venus. The absence of any notable attenuation in the intensity of emissions near the line of resonance absorption of water vapor λ = 1.35 cm can be interpreted as an indication that the maximum content of H_2O is not over 0.1%. The most probably chemical composition of the Venusian atmosphere corresponds to a value of mean molecular weight μ = 43.3. The chemical composition of the Venusian atmosphere, according to a /31 combination of results from all measurements, is presented in Table 3. In order to measure temperature and pressure, Venera 4-8 carried simple, reliable instruments for measurement of the heat-physical parameters of a dense gas by means of resistance thermometers and membrane (aneroid) manometers [1, 2, 34, 35].

The altitude profile of temperature on the sunlit side measured by Venera 8 is quite similar to the results of earlier measurements in the night atmosphere by Venera 4-7 (Figure 5). The temperature of the atmosphere at the surface was measured by Venera 7 and 8 as 747 ± 20° and 734 ± 8° K respectively.

The pressure at the surface, measured by Venera 7, was 90 ± 15 kg/cm^2. At the point of landing of Venera 8, the pressure was found to be 93 ± 1.5 kg/cm^2. The altitude variations in pressure in the Venusian atmosphere are also shown in Figure 5.

In the areas which they both covered (from 300 to 440° K in temperature and 0.6 to 7 kg/cm^2 in pressure), the measurements of the Venera spacecraft and the data of Mariner 5, produced by the radio refraction method as the spacecraft went behind the planet [94], are in good agreement.

Comparison with the data of Mariner 5, related to the distance to the gravitational center of the planet, indicates that the regions of landing of Venera 7 and 8 correspond to a planetocentric distance r = 6051-6052. These local values agree well /32 with available data on the mean radius of Venus, calculated from radar measurements.

As we can see from Figure 5, the experimental profiles of atmospheric parameters determined from the measurements of Mariner 5 cover the altitude interval between 35 and 90 km. Here also we see the calculated curves T(h), produced in the approximation of radiant equillibrium for a "grey" stratosphere [33], and according to the stricter recent measurements of Dickenson [83]. These latter measurements consider the effectiveness of heating of the atmosphere between 65 and 115 km due to absorption of solar radiation in the near IR area of the spectrum and refined characteristics of cooling due to radiation in the fundamental 15 μ band of CO_2. The resulting equillibrium temperature profile (dot-dash line) indicates a drop in temperature from 250° K at an altitude of 66 km to approximately $T_m \simeq$ $\simeq$ 160° K near 90 km, which agrees rather well with the experimental curve (the ambiguity and inversion nature of which in the area of the beginning of measurements of Mariner 5 (Figure 5) are determined by the selection of boundary conditions for integration of the dependence of index of refraction on height selected).

In contrast to the simple approximation of radiant equillibrium, leading to a minimum temperature value of about 195° K at an altitude of 105 km, according to the calculations of [83] a second temperature minimum T $\simeq$ 180° K is reached at about the 120 km level, with a slight peak in the area between at T $\simeq$ 190° K. An additional criterion for determination of the altitude dis- /33 tribution of atmospheric parameters in the entire area from approximately 60 to 120 km, which can be called the stratomesosphere by analogy with the Earth, is the estimate of the density of the atmosphere and the gradient of its change, based on the results of photometric measurements of attenuation of the radiation from Regulus (α Leo) as it was occluded by Venus in 1959 [213]. The characteristics produced at the level of eclipse (h_R = 120 km) place a definite boundary condition on the rate of decrease in temperature (scale of altitudes) in the area beneath that level, determining the intensity of "settling" of the atmosphere.

The T(h) profile below 60 km corresponds in general to the distribution of temperature in the atmosphere with convective equillibrium. The temperature gradient, within the limits of possible measurement errors of T and h, is near the mean adiabatic gradient $(dT/dh) \approx 8.6° \text{ km}^{-1}$.

A thermodynamic analysis of the curves of measurement of the gas state in the atmosphere of Venus at the corresponding temperature and pressure confirms this conclusion. However, certain peculiarities in the gas state are possible, particularly in the 15-37 km area, which is indicated by the results of analysis of the radio refraction profiles and microwave losses produced from the measurements of Mariner 5 [94]. It is interesting that below 40 km, according to the measurements of densimeters carried on Venera 4 and 5, significant deviations /34 were also observed from monotonic density change [151]. It can be assumed that relatively slight concentrations of impurities, particularly in the liquid or solid phases, which would have no influence on the molecular weight and therefore would not show in pressure measurements, might significantly influence the indications of densimeters, due to their operating principle.

The observed value of microwave attenuation cannot be explained by absorption by a mixture of CO_2 and H_2O alone. These losses were found to be about 10^{-3} db/km at the 37 km level for each of the components, i.e., one half or one third that required for agreement with the data of Mariner 5 (Figure 6). However, the microwave spectrum determined by terrestrial measurements is in general rather well explained by an atmospheric model with a surface pressure of 80-100 atm, consisting of CO_2 with a concentration of H_2O of about 10^{-3} [170]. To explain these peculiarities, we can assume the existence of additional impurities, the distribution of which by altitude is accompanied by phase conversions, so that they are localized at certain levels.

In a mixing atmosphere, this possibility is easily realized for condensing substances. With a surface temperature of Venus of about 750° K, many volatile components might go over from the lithosphere into the atmosphere and exist in it in the form of vapors and condensates at different levels. Possible equilibrium geochemical reactions for the lithosphere-atmosphere /35 system were discussed in detail by Lewis [136, 137] who, in particular, studied the conditions of formation of mercury-halogen clouds in the atmosphere, condensing at temperatures of from 250° K ($HgCl_2$) to 450° K (Hg_2I_2). Rasool [177] indicated the possibility of existence of such clouds, based on analysis of the attenuation of the Mariner 5 radio signals. We also cannot exclude the possibility of existence of ammonium compounds, if sublimiting at T > 330° K, but bonded with carbon dioxide, water, hydrogen chloride and other gasses at higher levels in the atmosphere of Venus.

Clouds

The assumption of various impurities in the atmosphere is directly related to the problem of Venusian clouds, concerning the structure and nature of which there is still no unanimous agreement.

The basic source of information currently available on the clouds consists of observations of the optical characteristics of the planet from the Earth, relating to the upper portion of the visible cloud layer (Figure 7). Based on these observations, estimates have been produced of the mean diameter of cloud particles (about 1.1 μ), characteristics of reflection (albedo) in various areas of the spectrum, index of refraction, volumetric scattering factor, etc. [40, 151, 119].

The combination of optical characteristics, together with data on the altitude profiles of temperature and pressure, however, do not allow us to determine the substance of which the Venusian clouds consist. Considering what we have already stated concerning the possibility of transition of various chemical elements and compounds from the lithosphere to the atmosphere, we cannot exclude a stratefied structure of the clouds, including various components. /36

It would seem most attractive to make the obvious assumption of water-ice clouds. Based on the measurements made by the Venera spacecraft, indicating rather high moisture content of the upper portion of the troposphere of the planet, water clouds (probably including solutions of certain salts, which is the case for terrestrial clouds as well) should exist regardless of the presence of condensates of other substances.

With an H_2O concentration of about 1%, the lower boundary of such clouds should be found at a level of 59 km, the effective thickness of the cloud layer them amounting to about 10-15 km. However, if the concentration of H_2O is less than 0.1%, the level of the beginning of condensation should be found at 68 km.

With $T_m \approx 160°$ K, sublimation would continue right up to about 110 km (Figure 8).

The strongest arguments against H_2O clouds include the absence of the depressions at 1.5 and 2 μ characteristic for ice, the excessive divergence in the index of refraction (polarimetric observations of Venus indicate $\eta \approx 1.45$, while for ice $\eta \approx 1.31$), the slight transparency of the clouds for waves with $\lambda > 0.6$ μ; /37 the low concentration of water vapor according to spectroscopic data, if we assume that the level of formation of the H_2O bands is higher than the level for which the brightness temperature of the planet is measured [108, 108, 172, 188].

In the light of the available spectroscopic and polarimetric data, many other compounds earlier assumed such as C_3O_2, SiO_2, carbohydrates and various chlorides such as $FeCl_2$, NaCL, NH_4Cl are also contradicted [0 (sic -- tr.), 151, 110]. Recently, the interesting suggestion has been published that the clouds are enriched in an aqueous solution of HCl in comparison to which relatively low content in the gas medium [138]. This is based on the assumption of the presence of a six-molar (25%) solution of hydrochloric acid in the clouds so that the spectroscopic data on the content of H_2O and HCl correspond to the condition of phase equillibrium. One favorable factor here is the fact that the index of refraction of an aqueous solution of HCL increases with decreasing temperature, approaching the measured value at the upper boundary of the Venusian clouds. These same considerations speak in favor of another curious hypothesis -- the enrichment of the clouds with an aqueous solution (about 80%) of sulfuric acid [216]. In this case, one serious difficulty is avoided, since we can match the estimates of the water vapor pressure at the level of formation of the spectral lines ($T \approx 235°$ K, $fH_2O \approx 10^{-4}$ mb) to the results of direct measurements of absolute moisture content in the underlying atmosphere. /38 The reflection characteristic (albedo) of Venus in the near IR (1.7-4.0 μ) area of the spectrum and the emission spectrum in the 8-13 μ area agree with this assumption satisfactorily (see Figure 7). We can also explain the proposed liquid-drop state of the clouds, indicated by polarimetric measurements [138] and the reason for the extremely low content of sulfate compounds according to the data of terrestrial spectrometry (see Table 3). The latter compounds in this case should be removed from the atmosphere by reactions, possibly including photodissociative decomposition of elementary bromines. It is curious that the required quantity of H_2SO_4 for formation of visible clouds in this case is slight, agreeing with the cosmic distribution of sulfur and its arrival from the depths of the planet due to volcanic exhalations.

Thus, many data seem to speak in favor of the hypothesis, which at first glance seemed rather exotic, and allow us to eliminate the contradictions found in other assumptions. Nevertheless, more detailed analysis of this fresh and interesting idea is of course required, followed by direct measurements, which will allow us to obtain the best answer to the question of the nature of the Venusian clouds.

Illumination

The question as to whether sunlight penetrates to the surface of Venus or is fully absorbed by the dense atmosphere and clouds has been the subject of discussion for many years. The /39 degree of transparency of the atmosphere in the visible area of the spectrum will determine both the conditions of illumination at the surface and the nature of the high temperatures on the planet. Therefore, the answer to this question is important; however, it has only been answered very recently as a result of direct measurements below the clouds visible from the Earth. These measurements were performed by the Venera 8 automatic spacecraft using special photometric devices with sulfur-cadmium photoresistors as receptors. These devices retain their efficiency following extended exposure to temperatures up to 500° C and pressures up to 100 atm. The range of spectral sensitivity of the receptor is from 0.4 to 0.8 μ, with its maximum at 0.62 μ. The index of the sensor allowed it to record both direct rays at all zenith angles and diffuse radiation [4].

The results of the measurements, performed with a zenith angle of the sun at the point of landing of 84.5 ± 2.5°, are shown in Figure 9. This figure shows the nature of attenuation of solar energy (in w/m^2) in the atmosphere of Venus from an altitude of about 50 km right down to the surface. As we can see, the nature of attenuation of the radiant flux is uneven with altitude. From the upper boundary of the visible clouds (about 70 km) to the level of beginning of measurements, light is attenuated by a factor of approximately 7, while between 50 and 35 km it is attenuated by an additional factor of approximately 3, followed by an additional attenuation factor of /40 approximately 4 in the layer below 35 km. This means that as the physical density of the atmosphere increases, its optical density decreases. The break in the curve near 35 ± 3 km is quite characteristic. The attenuation of light from this altitude to the surface is explained quite well by molecular (Rayleigh) scattering in a carbon dioxide atmosphere at the ambient pressure. Above 35 km, we must assume the presence of aerosol scattering or significant true absorption in order to explain the nature of the attenuation. The models calculated under these two assumptions are satisfied with high values of optical thickness $\tau_0 \approx 50$ and unit scattering albedo $\omega \approx 1$, respectively, or for $\tau_0 \approx \tau_{rayl} = 3.5$ and $\omega_0 \approx 0.9$. Consideration of the degree of elongation of the scattering indices has a certain influence on these estimates [28].

Optical measurements in the atmsophere have served as an additional source of information on the structure of the clouds on Venus. The significant attenuation of light right down to 35 km can be interpreted as an indication that the cloud cover extends down to this level. However, the level of the beginning of condensation of H_2O, as we have seen, is almost 25 km higher. This disagreement can be explained if we recall the possibility of existence of phase transitions, and in particular of mercury-halide clouds, the Lewis model of which [136] is also shown in Figure 9. The boundary of HgS clouds in this case would fall at an altitude of about 35 km. Another possibility is the existence /41 of liquid-drop water (precipitation of "rain") approximately down to this level (dot-dash line on Figure 7), near which the water-steam phase conversion would occur at the corresponding P and T [4].

If we assume slight deformation of the spectral composition of solar radiation upon penetration through the atmospheric mass, the conversion from the measured radiant energy to values of illumination can be performed using the conversion factor $\zeta \approx 350$ lx/w$\cdot$m^{-2}, determined from the results of calibration. In this case, the expected illumination at the surface at the point of landing should be about 300 lx, or at zero solar zenith angle -- over 3000 lx. Thus, although only about 1% of the light flux striking Venus reaches the surface, this would be sufficient to create significant illumination (approximately the same as an extremely cloudy day on Earth).

The light reaching the surface is repeatedly scattered and is diffuse. As yet, it is difficult to estimate reliably the range of visibility under such conditions, or the color characteristics. These characteristics are not only physical, but also of practical interest, particularly from the standpoint of the possibility of certain curious effects, resulting from the strong refraction of light rays in such a dense gas. If the transparency of the atmosphere is sufficient, the horizon would seem elevated /42 in all directions, and an observer on the surface would see the illusion of standing in the bottom of a giant bowl.

Thermal Mode

The data from measurements of the solar radiant energy in the atmosphere of Venus and the results of calculation of the transfer of departing radiation confirm the hypothesis set forth by C. Sagan in 1960 [185] that the origin of the high temperature at the surface of the planet is most probably to be found in the greenhouse effect. The physical essence of this mechanism is rather simple. Visible solar light, only partially absorbed by the atmosphere and clouds, reaches the surface of the planet, heating it, and the heated surface radiates longer infrared waves, which are retained by the dense Venusian atmosphere. A similar mechanism, but much more strongly expressed, occurs in the terrestrial atmosphere and is widely used in greenhouses, which also prevent convective heat transfer. Calculations have shown that even if a slight portion of the solar radiation reaches the surface of Venus, carbon dioxide gas with a very slight quantity of water vapor would create a strong screening effect for departing thermal radiation. With increasing temperature and pressure, the degree of screening increases. The conditions on the planet apparently developed as a result of gradual self-heating and now correspond to an /43 equillibrium state. Obviously, this is not only a temperature equillibrium, but also a geochemical equillibrium, corresponding to the measured content of carbon dioxide gas and atmospheric pressure. Of course, the Venusian clouds, reflecting a certain portion of the departing radiation back from their lower boundary, also have some influence on the distribution of the field of thermal radiation in the atmosphere.

The heat fluxes for measured atmospheric parameters of Venus change significantly with altitude (Figure 10) [37]. As we see, near the surface the gas retains radiation so strongly that the surface makes practically no contribution to the departing heat flux. Radiant equillibrium is apparently achieved only near 40-50 km. The thermal balance at lower altitudes can be provided only by additional heat transfer. Since the measured temperature profile is near adiabatic, it is most probable that this additional mechanism of heat transfer is convection.

Studies of the convective activity in the atmosphere of Venus have indicated that the most probable rate of convection in the lower layers of the atmosphere of Venus is less than 0.05-0.2 m/sec [3]. These same conceptions are indicated by estimates produced independently by calculation of the vertical currents using equations relating the aerodynamics of the para- /44 chute descent of the Venera spacecraft to measured values of P and T. It should be noted in this case that convection can reach higher areas of the atmosphere, so that the convective zone becomes greater than the area of atmospheric instability. Although modeling has as yet been performed for an area limited to approximately 40 km altitude, we can assume that convective transfer is effective throughout the entire area of the troposphere and, in particular, that it is important in the formation of the structure of the Venusian clouds.

Due to the tremendous heat content of the Venusian atmosphere, it should have great thermal inertia, so that the difference between the day and night sides is very slight: the maximum diurnal variation at the surface is less than 1°.

The results of measurements of the temperature by the Venera 8 spacecraft on the sunlit side serve as convincing confirmation of these theoretical assumptions. The equallization of temperature during the day, and also between the equatorial and polar areas, is confirmed by the results of recent measurements of the brightness temperature of the planet by terrestrial radiointerferometry at wavelengths of 11 and 13 cm, relating to the surface and the lower atmosphere respectively [95, 197]. According to these results, there is no significant phase ($\Delta t_f < 12 \pm 6°$) or latitude ($\Delta T_\ell < 18 \pm 9°$ K) change in temperature across the disc of Venus. The infrared brightness temperature also is essentially independent of phase. Averaging over the disc yields $T_b = 220 \pm 10°$ K, corresponding to an altitude of about 70 km, and diurnal changes in temperature near this level are also practically nil [163]. /45

Dynamics of the Atmosphere

Problems of the dynamics of the Venusian atmosphere, particularly large-scale planetary circulation, are directly related to the problem of the thermal mode of the atmosphere. One mechanism of this type is the model of deep circulation suggested by R. Goody and A. Robinson [104], until recently considered a probably mechanism for explanation of heat exchange on Venus in the case of nontransparency of the atmosphere below the clouds for solar rays. Other attempts have also been made to calculate the structure of planetary circulation and estimate theoretically the intensity of atmospheric movement, based on methods of numerical modeling or the use of similarity relationships [12, 19]. Apparently, latitude-longitude circulation plays a significant role in the thermal mode of the planet. In particular, transfer of hot, dense gas in the meridianal direction should facilitate transfer of heat into the polar regions.

Of extremely great significance for investigation of the dynamics of the Venusian atmosphere are the results of measurements of the radial velocity of sectors of the parachute descent of the Venear spacecraft, which yielded interesting data on the /46 nature of horizontal motions, as well as some ideas concerning the structure of small scale (turbulent) fields [160, 166, 168]. The results of all measurements of horizontal velocity are shown in Figure 11. They relate to local areas of the descent of each spacecraft. However, due to the tremendous heat capacity of the Venusian atmosphere already mentioned and the fact that the time of thermal relaxation at the surface is on the order of 10^{10} sec which results, we can believe that equalization of irregularities of the thermal fields occurs due to large-scale motions rather than due to local winds. From this point of view, the data of Figure 11 must naturally be looked upon as reflecting to some degree the structure of global circulation on the planet.

Our attention is drawn by the rather convincing agreement of individual measurements. They indicate that there is stable zonal circulation in the direction corresponding to the natural rotation of the planet, at least above 30 km. The most complete measurements were made by Venera 8, which detected the highest wind speeds on the illuminated side near the morning terminator. As we see, the horizontal component of wind velocity varies strongly with altitude: at altitudes of about 45-50 km, it reaches almost 100 m/sec, decreasing to less than 1 m/sec below 10-12 km. The altitude range between 18 and 30 km is interesting, since the wind speed remains almost unchanged in this range, whereas above and below this area the gradient reaches 5 m/sec·km.

The very low wind speeds in the surface layer of the atmosphere indicate immediately that there cannot be much dust in the atmosphere. This, as we have seen, agrees with the results of measurements of illumination. As concerns the higher altitudes, we gain an impression of direct relationship between measured wind speed and the mechanism of stratospheric circulation, manifested as drift of the so-called "ultraviolet clouds." /47

When terrestrial observations are made in the ultraviolet area of the spectrum, individual contrasting details are seen which cannot be seen in the visible area of the spectrum (Figure 12). It has been established that the movement of these details across the disc of the planet is much more rapid than the natural rotation of the planet, by approximately 60 times, corresponding to a mean drift rate of about 100 m/sec [63, 201]. We note that leading rotation of the atmosphere on the Earth, with a velocity ratio of not over 1.2-1.4, is found only at significantly higher altitudes -- 150-400 km.

The observed irregularities in the Venusian clouds in the ultraviolet range are located some 25 km higher than the boundaries of the cloud cover in visible light. The periodic repetition of details apparently reflects the general nature of global circulation in the troposphere and stratosphere of Venus.

Upper Atmosphere and Space Around the Planet

The structure of the atmosphere of Venus at high altitudes, /48 in the areas of the thermsophere and exosphere, and the physical structure of fields in space around the planet represent a separate problem. The data available on the upper atmosphere of Venus are based on the results of measurements performed by the Venera 4 and Mariner 5 spacecraft, produced during a time corresponding to conditions of moderate solar activity. The value of exospheric temperature T ≈ 650° K for these conditions corresponds to the most probable estimate produced from the results of measurement of resonant emission in the Lyman alpha spectral line of hydrogen (L_α 1216 A) [55]. The results of theoretical modeling agree well with this estimate and indicate the probable existence of a temperature difference on the day and night sides of the planet of some 400 to 900° K [195, 84], as well as the possibility of significant variation in T as a function of the phase of the 11-year solar cycle.

Spectrophotometric measurements of resonant scattering in the characteristic lines of atomic oxygen, made by high altitude rockets and spacecraft [132, 154], have been used as a basis for estimates of the O content in the upper atmosphere of Venus. They are of great interest, since they determine the degree of photodissociation of carbon dioxide gas, the primary component of the atmosphere of Venus, by the ultraviolet radiation of the sun, forming O and CO. If the upper atmosphere of Venus were in photochemical equillibrium, then as simple calculations show, at altitudes of 200-300 km atomic oxygen would be the predominant component, as is the caseon Earth, where it is formed as a result of dissociation of molecular oxygen. However, the content of O /49 is estimated as 1-10% of the total density [89]. This leads to the assumption of high effectiveness of reverse recombination mechanisms in the thermosphere of Venus, preventing the accumulation of oxygen due to the dissociation of CO_2. The assumption of the predominant concentration of CO_2 up to altitudes of around 200-300 km is confirmed also be theoretical calculations of the profile of electron concentration in the ionosphere of Venus and their comparison with the results of measurements by Mariner 5 [145, 149, 150]. These results are shown in Figure 13. The bundles of lines characterize the slopes of profiles for calculated values of the altitude scale corresponding to various ions for several values of plasma temperature t_p. As we can see, up to 300 km the best agreement is provided for the CO_2^+ ion. The maximum electron concentration in the ionosphere on the day side, reaching $5.5 \cdot 10^5$ cm^{-3}, corresponds to an altitude of 142 km, i.e., slightly over half as high as the maximum of the F_2 layer in the terrestrial ionosphere (in which the O^+ ion predominates), with approximately half the electron concentration. In the night ionosphere, the electron density $n_e \lesssim 10^3$ cm^{-3}.

Many attempts have been made to find an adequante mechanism to explain the primarily carbon dioxide composition of the thermosphere of Venus, as well as the thermosphere of Mars, where the situation is similar. Greatest progress has been achieved in the study of the Martian thermosphere, due to the remarkable results of ultraviolet spectrometry from spacecraft /50 achieved by Bart and his colleagues [56, 57]. In particular, the discovery of strong emissions in the radiation spectra of the Martian atmosphere similar to the resonant emission of O belonging to the system of Cameroon bands of CO and the bands of CO_2^+, was quite unexpected. This indicates significant losses of energy from the atmosphere by radiation in the ultraviolet area of the spectrum, in addition to the significant cooling in the long wave band, primarily due to oscillating conversions of CO_2. We can assume that such mechanisms are also characteristic for the thermosphere of Venus which, incidently, explains the comparatively low temperature of the upper atmosphere of the two planets. As concerns the retention of primary concentration of CO_2, the idea of the intensity of dynamic processes of macrocirculation transfer from the day side to the night side and turbulent diffusion is currently widely accepted. In other words, atomic oxygen is rapidly carried away from the areas of dissociation [84, 195]. In the denser, lower-lying atmosphere, recombination processes are significantly more effective. Intensive turbulent diffusion assures constant delivery of molecules of carbon dioxide to the upper atmosphere. Although the required values of turbulent diffusion factors are rather high (10^7-10^8 cm^2/sec, i.e., approximately an order of magnitude greater than the figures for the Earth), they are quite possible for the conditions of the upper atmospheres of Venus and Mars. Here, we must also explain the actual sequence of chemical con- /51 versions accompanying the processes of circulation or diffusion mass transfer, considering the maximum concentrations of the components participating and the rate constants of the corresponding reactions.

According to existing estimates, the effectiveness of the most probable mechanism of recombination of atomic oxygen drops significantly below 300 km. This, obvious, should lead to appearance of a comparatively thin layer of atomic oxygen, with helium having a certain influence above this layer. The measured electron concentration profiles in the night atmosphere of Venus, shown in Figure 13, can be explained by photoionization of helium on the day side at a rate of $3 \cdot 10^7$ $cm^{-2} \cdot sec^{-1}$ over 250 km with subsequent horizontal transfer of He^+ ions to the nonilluminated hemisphere. If the delivery of helium to the Venusian atmosphere due to radioactive decomposition of uranium and thorium within the planet corresponds approximately to its delivery to the atmosphere of the Earth (about $3 \cdot 10^6$ atm.$\cdot$cm$^{-2}\cdot$sec^{-1}), the necessary balance between delivery and thermal dissociation of helium is provided if we assume additional transfer of about 10% of the quantity of He^+ ions formed on the day side of the planet by the solar wind [146].

As we can see from Figure 13, above approximately 1000 km the atmosphere of Venus apparently becomes primarily hydrogen. The hydrogen corona of Venus, directly measured by spacecraft /52 [55, 132], is similar to the hydrogen corona of the Earth, but at the lower exospheric temperature it is smaller. Measurements of Mariner 5 showed a curious peculiarity of hydrogen emission from the day side of the planet -- a rapid increase in the intensity of the glow in the direction toward the limb (in the altitude range from 3000 to 450 km), corresponding to a decrease in the scale of altitudes by approximately a factor of two. Although this high intensity of glow from the day side of the planet was not confirmed by the rocket experiments of Moos et al. [154], various hypotheses have been set forth to explain this interesting phenomenon. The most probable hypothesis is based on the significant content of deuterium in the base of the hydrogen corona of Venus. However, it requires that we assume that the relative content of deuterium on Venus $n_D/n_H \simeq 0.1$, which is significantly greater than in the atmosphere of the Earth. This ratio is difficult to explain within the framework of the mechanism of thermal fractionation of hydrogen and effects at the base of the exosphere. However, for a planet practically free of a regular magnetic field (its intensity is some 1/3000 that of the Earth [18]), one additional and quite effective mechanism might be transfer of particles ionized by solar ultraviolet radiation by the electric field arising in the induced ionopause of Venus on the day side as solar plasma flows toward the planet.

The concept of the "induced ionopause" is illustrated by Figure 13, which shows a sharp (by almost three order of magni- /53 tude) drop (cutoff) of electron concentration in the hemisphere illuminated by the sun, in contrast to the even drop on the night side. This results from the formation of a shock wave in the area where the pressure of the solar wind is comparable to the pressure of the induced magnetic field. The ionopause on Venus is similar to some extent to the magnetopause on the Earth, which prevents direct penetration of the solar plasma into the magnetosphere -- the area of the regular geomagnetic field. Therefore, the magnetopause is located significantly further from the surface, at a distance on the order of 10 Earth radii.

Since Venus has no strong perturbing influence on the structure of the interplanetary field, it is natural to assume that the solar wind flowing around it practically does not change its characteristics on the night side [205].

The nature of the physical structure of the atmosphere of Venus up to an altitude of about 1000 km is summarized in Figure 14 according to model [36], containing the primary physical parameters of the atmospheric gas. The right upper portion of the figure shows the flow of the solar wind around the planet schematically, indicating the parameters of the unperturbed flow.

Origin and Evolution

The hypothesis of the single origin of all the planets of the solar system from a gigantic protoplanetary gas-dust cloud, naturally, leads us to seek common features among the planets /54 of the Earth group, more or less similar characteristics. However, the results of investigations of the past decade have provided convincing evidence that the Earth, Mars, Venus and Mercury differ strongly from each other. These differences can be explained to a certain extent by differences in the current stage of evolution of the planets. We can imagine with some reliability how the Earth developed. The natural conditions on the Earth millions of years ago were doubtless different from now. The nature of this evolution depends on many conditions, primarily the geometric and mechanical characteristics of the planet, the distance to the sun, changes occurring within the planet, fragmentation of rock. These processes are accompanied by the formation and evolution of the planetary atmosphere, which therefore contains the most important characteristics of each stage.

The gas composition of the atmosphere of the planets of the Earth group was formed primarily due to volcanic emissions, accompanied by processes of differentiation of the substance of the planet into envelopes due to heating of the interior by the heat of radioactive decay. Within the planet, water vapor and carbon dioxide make up the primary fraction of volcanic gasses. It is therefore not surprising that these gasses, as well as the carbon monoxide, hydrogen chloride and hydrogen fluoride determined by spectroscopic measurements are present in the atmosphere of Venus (nor is it surprising that the possibility of sulfurous gasses, confirming the hypothesis of clouds of H_2SO_4, may be present). It is probable that the atmosphere of the Earth had a similar composition over a billion years ago. /55 However, processes of photosynthesis and the appearance of free oxygen due to the development of the biosphere apparently had a decisive influence on the formation of the terrestrial atmosphere. This in turn resulted in the oxidation of ammonia, also contained in volcanic gasses, liberating large quantities of nitrogen into the atmosphere, while the carbon dioxide, hydrogen chloride and hydrogen fluoride and sulfur compounds entered into reactions with the biosphere, hydrosphere and the solid substances of the planet. With the moderate surface and atmospheric temperatures, the Earth retained its water, most of which was concentrated in the oceans [7, 8].

Probably, the greater proximity of Venus to the sun caused the evolution of its atmosphere to be different. Apparently, the primary factor leading to the conditions of today was the loss by the planet of its water. The question of water is, probably, the key question in the problem of the evolution of Venus.

If we eliminate the improbable assumption that water was not liberated from the core of the planet in volcanic activity during its evolution as apparently occurred on the Earth, we must understand why the water content in the atmosphere of Venus is at least 1000 times less than on Earth. One possible explanation is that the temperature of the coldest area in the upper atmosphere of Venus (the mesopause) is somewhat higher, and that hard ultraviolet radiation can penetrate more deeply, than on /56 Earth. The result would be more intensive decomposition of water into oxygen and hydrogen and more energetic dissipation of light hydrogen from the atmosphere into space. The oxygen would then be bonded by the solid substances on the surface of the planet.

High temperature, high pressure, very low content of water and almost total absence of oxygen -- all of these modern peculiarities of the atmosphere of Venus are interrelated and interdependent. As the temperature rises, more water enters the atmosphere, and dehydration increases the content of carbon dioxide which, in turn, should facilitate a further increase in temperature due to the greenhouse effect. At high temperatures, there can be no biosphere in the form familiar to us, while the absence of a biosphere essentially eliminates the possibility of a high content of free oxygen in the atmosphere.

The comparative content of the commonest volatile components on Earth and on Venus is presented in Table 5 [118]. As we see, the quantity of carbon dioxide on the Earth is approximately the same as on Venus. However, in the terrestrial atmosphere its quantity is negligible (0.0003 kg/cm^2), the main mass being found in the upper envelope of the solid Earth. This relationship in the contents of CO_2 between atmosphere and lithosphere corresponds to the equillibrium state at the current temperature of the Earth, determined by reactions between carbonates and silicates in the presence of liquid water. The carbon dioxide on the Earth is bonded into carbonates in sedimentary rock, primarily due to /57 the activity of living organisms. On the hot planet Venus -- with no water -- carbon dioxide could not go over into the lithosphere and was retained in the atmosphers, creating the extremely high pressure of the gas envelope of the planet. If the temperature on the Earth increased to the temperature of Venus, the pressure of the terrestrial atmosphere would become still higher than the current atmospheric pressure on Venus. The reason is that the pressure of some 100 atmospheres resulting from the liberation of carbon dioxide from carbonates would be supplemented by an additional 300 atmospheres, corresponding to the mean depth of the world ocean, due to the evaporation of the water in the ocean.

The peculiarities of the evolution and heat exchange, the nature of the clouds and the surface, do not exhaust the problem of Venus which containues quite justifiably to be called the mystery planet, in spite of the tremendous successes achieved in the past few years of study.

Venus hides many secrets, the discovery of which will doubtless enrich planetology with new fundamental knowledge. The thickness of the gas envelope, its unique thermal regime, the unusual nature of its rotation -- these and other peculiarities make Venus truly different among the family of planets in the solar system. What has caused these unusual conditions? Is the atmosphere of Venus a "primeval" atmosphere, characteristic of a young planet, or did these conditions arise later, as a result of irreversible geochemical processes caused by the proximity of Venus to the sun. These questions are worthy of close attention and will require further comprehensive study.

MARS

Mars is the fourth and last of the planets of the Earth group, in order of increasing distance from the sun. It moves in an external orbit (contrast to the "inner planets" -- Mercury and Venus), and therefore turns its day side toward the Earth as it approaches us and is quite easily seen. Nevertheless, the possibility for producing new information by observation from the surface of the Earth is limited. /58

In recent years, our knowledge of Mars has grown at unforseen rates, primarily due to the use of space technology.

Only spacecraft can observe Mars from close up. The advantages are obvious: a great increase in detail of images of Mars; elimination of the interference of the Earth's atmosphere, since observations are performed from beyond the atmosphere; light apparatus used in place of huge telescopes. All of this allows studies to be made which are simply impossible to perform from ground observatories. The first attempts to utilize these advantages led to new discoveries. Up to 1971, all automatic spacecraft sent to Mars were flyby vehicles, and the great capabilities of their apparatus were strongly limited by the short span of time they spent near the planet. The desire to use the advantages of spacecraft more fully led in 1971 to the more complex equipment, designed to place spacecraft in orbit around Mars. On 16 November, the Mariner 9 spacecraft of the /59 USA began to orbit Mars, followed by the Soviet spacecraft Mars 2 and Mars 3 on 27 November and 2 December. On 2 December, the Mars 3 descent vehicle made the first soft landing on the surface of the planet. The Soviet automatic spacecraft landed in the Martian desert Phaethontis at about 45° south latitude and 158° west longitude. Unfortunately, the difficult landing conditions prevented performance of the planned sequence of measurements.

At the time, a powerful dust storm of global scale was occurring on Mars. The clouds of dust, rising in the Martian atmosphere, made it almost opaque to rays in the visible portion of the spectrum. Therefore, on the first photographs transmitted by Mars 3 and Mariner 9, the surface of Mars looks completely smooth, without noticeable contrast. The limb of the planet is clearly seen (indicating the good accuracy of the image transmitted), the terminator (boundary between the day and night hemispheres) can be clearly seen, but no relief details are visible. On larger-scale photographs, one can distinguish the wavy surface of the clouds and over the horizon a thin layer of cloud is seen as a narrow bright strip. Local clear spots began to appear in the second half of December, satisfactory atmospheric transparency was observed after 23 January, and the atmosphere became fully transparent in February. The dustiness of the Martian atmosphere at first prevented photography of the surface of the planet. However, a unique opportunity was provided to study a very strong Martian storm from close up.

Due to the use of spacecraft and new methods of observation from the surface of the Earth, the quantity of information on /60 Mars has increased tremendously in recent times. In particular, the television images of the surface of Mars and of its satellites transmitted by Mariner 9 are of great interest. Combined analysis of the results of the mutually complementary experiments performed by the three artificial satellites of Mars has contributed greatly to the understanding of the physical and geological-morphological peculiarities of this planet and the physics of the space around it.

Some Global Characteristics of Mars

Dimensions, Figure and Gravitational Field of the Planet

The results of measurement of the radius of Mars by different methods agree well with each other. A summary of the latest optical measurements and an extensive bibliography are contained in [8]. The results indicate an ellipsoid with $R_{eq} = 3398 \pm 3$ km, $R_{pol} = 3371 \pm 4$ km.

The combination of results of terrestrial radar during the oppositions of 1967, 1969 and 1971 [168] has indicated $R_e = 3394 \pm 2$ km. This is the mean radius within the limits of the tropical belt of the planet.

Apparently, measurements of the radius of the planet on the basis of the blocking of radio signals from spacecraft flying behind Mars have yielded the greatest accuracy (mean square error on the order of 1 km). Measurements from Mariner 9 have shown that the physical surface of Mars can be approximated by a triangular ellipsoid $x^2/A^2 + y^2/B^2 + z^2/C^2 = 1$, with a polar radius $C = 3375.45$ km, and in the plane of the equator: large half axis $A = 3400.12$ km, small half axis $B = 3394.19$ km, longitude of large axis $L_A = 99.7°$ [66]. Significant asymmetry of Mars along the polar axis has been discovered: the level of the surface almost throughout the southern hemisphere is 3-4 km higher than /61 in the northern hemisphere.

Precise analysis of the movements of Mariner 9 in its orbit around Mars has revealed heterogeneity of the gravitational field of the planet [139]. These heterogeneities indicate local fluctuations in density beneath the surface. The results of measurement can be arbitrarily expressed in the form of positive and negative mass concentrations or equivalent altitudes of the physical surface of Mars over the surface of a spherical body of homogeneous density. Some mass concentrations are easy to identify with local fluctuations in the radius of the planet.

The degree of polar compression of Mars determined by occultation of radio signals does not agree with dynamic compression (i.e., the compression of the ellipsoid of inertia of the planet) determined from the precession of the orbits of the satellites of Mars and calculated on the basis of the hydrostatic theory in the model of a homogeneous Mars. The disagreement can be explained by convection of solids within Mars [183].

The total mass of the planet, calculated from the motion of its satellites [215], is some $6.423 \cdot 10^{23}$ kg. Analysis of the motion of the Mariner 6 and 7 flyby spacecraft allowed American specialists to refine the constant consisting of the product of the constant of gravity times the mass of the planet [49]: $GM_{♂} = 42{,}828.1 \pm 1.38$ km^3/sec^2. The mass of the planet, unfortunately, can be concluded from this expression only with a loss of accuracy, since the constant of gravity itself requires refinement. Not more than four significant digits can be given with confidence, and figures are usually limited to this accuracy.

The parameters derivative from the mass and radius are : mean density of the planet around 3.94 g/cm^3; acceleration of the force of gravity on the surface of Mars 38% of its value on Earth, critical velocity 5.0 km/sec. /62

Magnetic Field

The magnetometer installed on the Mariner 4 flyby spacecraft (1965) to determine the dipole moment and properties of the Martian magnetosphere reported a jump in intensity of 5 gamma near the planet. The experimenters assumed that this jump is related to passage through the leading edge of a shock wave in the solar wind, not to the field of the planet. Based on the results of this experiment, estimates of the upper limit of magnetic moment of Mars indicate that it is 10^{-3}-$2 \cdot 10^{-4}$ times the terrestrial field [203].

Ferroprobe magnetometers on Mars 2 and Mars 3 (1971-1972) recorded a three-component change in field intensity in the orbital sections closest to the planet, exceeding the natural background of the interplanetary field in this region at the point of the maximum on the magnetogram by 7 to 10 times [17]. It is possible that the effect observed was caused by reinforcement of the magnetic field of the solar wind due to two factors: first of all, currents induced in the ionosphere of the planet, and secondly, compression of the plasma between the shock wave and the planet. However, in the opinion of Sh. Sh. Dolginov et al. [17] who performed the experiment, the data available on the topology and measured magnetic field can be best coordinated with the data of K. I. Greenhouse on the intensity of the solar wind and data on the position of the shock wave near the planet only if we assume the existence of a Martian magnetic field with a dipole moment of $2.4 \cdot 10^{22}$ Gauss$\cdot$cm^3 with an intensity at the magnetic equator of about 60 gamma, i.e., $2 \cdot 10^{-3}$ times the terrestrial field.

Parameters of Axial Rotation and the Martian Seasons /63

Telescopic observations of several generations of astronomers provided the first source of information on the direction of the axis and the rate of diurnal rotation of Mars. Axial rotation occurs at a constant angular velocity relative to the fixed stars. The sidereal period is equal to 24 hours 37 minutes 22.668 seconds. The length of a solar day varies slightly due to the unevenness of the movement of Mars in its orbit, averaging 24 hours, 39 minutes, 35 seconds. The number of solar days in a Martian year is 668 2/3, one less than the number of stellar days.

The axis of rotation of Mars is tilted from the perpendicular to the plane of the orbit by 25°, i.e., almost the same as is true for the Earth. However, the similarity is limited to the tilt, and does not include the direction of the axis of diurnal rotation. The polar axis of Mars is tilted with its northern end in the constellation Cygnus, at the point with the following coordinates: right ascention 317.3° ± 0.3°, declination +52.6° ± 0.2° (epoch 1971.9, equinox 1950.0) [139]. There is no notable star near the pole which could act as a north star.

The considerable inclination of the plane of the Martian equator to the plane of the orbit means that the northern and southern hemispheres of the planet receive varying amounts of solar heat: in some parts of the orbit, the northern hemisphere is primarily illuminated and heated, while in other parts it is the southern hemisphere. In other words, the change of seasons occurs on Mars.

At each time of year, the sun passes approximately the same height in the Martian sky as in the corresponding latitudes on Earth. However, in contrast to our seasons, the Martian northern /64
seasons differ quite markedly from the southern seasons in their length and temperature conditions. Spring and summer in the southern hemisphere of Mars are considerably shorter than spring

and summer in the northern latutides (Table 4), due to the considerable ellipticity of the Martian orbit and the resulting differences in the rate of travel of the planet over different portions of its orbit.

The significant difference in duration of the warm time of year in the two hemispheres of Mars is compensated for by the difference in brightness of solar illumination, resulting from the cyclical changes in the distance of the planet from the sun, and the mean temperature at the subsolar point and over the entire day hemisphere is 25-30° higher [at perihelion -- tr.] than at aphelion. This leads to differences in the climate in the northern and southern hemispheres.

The Martian calendar (if we construct it like ours and identify dates by the argument of declination of the sun) would show the aphelion at the end of May, the perihelion in early December. Thus, autumn and winter in the northern latitudes on Mars are less severe than in the corresponding southern latitudes.

The Atmosphere of Mars

Optical Properties

During visual observations by telescope, the atmosphere of Mars in the low and moderate latitudes most frequently appears transparent, with yellow turbidity and white clouds visual only occasionally. When observed through a blue filter, the atmosphere scatters sunlight quite strongly, and the details of the surface of the planet are poorly seen. Incidentally, some authors [171] explain the effect of reduced contrast with decreasing wavelength of reflected light by peculiarities of the color of the surface itself. Nevertheless, during terrestrial telescopic photography on unsensitized photographic film, sensitive only to blue, violet and ultraviolet light, most frequently all that can be seen is a cloudy fog of uneven density with extremely bright spots along the edges of the disc of the planet. /65

Pressure at the Surface

The ability of the Martian atmosphere to raise and hold dust in the suspended state for a long period of time creates an impression of significant gas density. This impression, however, is false, and was one reason for confusion of long standing. Rather rough estimates of the atmospheric pressure at the surface of Mars (generally expressed in millibars in planetary astronomy) until 1963 averaged around 80 mb (60 mm of mercury according to an aneroid barometer). The use of improved methods of remote measurement by both terrestrial and spacecraft-borne apparatus in recent years has indicated that the true pressure is 10 to 20 times less than was earlier thought, some 200 times less than on Earth. Here the normal atmospheric pressure at sea level is 1013 mb. On Mars, it varies from 3 mb at high altitude (about 1 mb on the highest peak) to 10 mb in the lowlands [74, 128]. The atmospheric pressure may vary, as listed in the section on barometric altitudes of relief.

Chemical Composition of the Lower Atmosphere

The primary component, carbon dioxide or CO_2, can be easily identified by the characteristic lines in the spectrum of the sunlight scattered by Mars. The abundance of gasses in planetary atmospheres is usually expressed in the form of the thickness of a layer, adjusted to a pressure of 1 atm. Many new estimates by various authors indicate that approximately 75 ± 15 m·atm CO_2 is present in the Martian atmosphere. Estimates and bibliographies are presented, for example, in [41] and in [217]. Terrestrial high resolution spectrographs have allowed us, using Doppler shift, to separate from the background of great telluric bands some weak details delonging to Martian water vapor [123]. This result has been confirmed and refined by new terrestrial observations [193]. Attempts were made to use the artificial satellites of Mars to study the moisture content of the lower atmosphere, not averaged over the entire visible portion of the day hemisphere, but rather for individual areas of the planet [74, 155]. /66

The content of H_2O in the Martian atmosphere undergoes seasonal variations in each hemisphere of the planet and changes from an indetectable quantity to some tens of microns of precipitated water. The wettest region in 1972 was the north polar area during the northern spring, where the atmosphere was found to be saturated with water vapor (i.e., 100% relative humidity) with some 20-30 μ of precipitated H_2O [74].

Terrestrian Fourier spectroscopy using a Michelson interferometer has been used to detect carbon monoxide or CO [122] in a quantity of 5.6 ± 1.0 cm·atm, i.e., less than 0.1% by volume. A new estimate [218] of the quantity of CO disagrees with earlier estimates, showing 42 ± 15 cm·atm.

In 1968, a report appeared [60] on the discovery of molecular oxygen on Mars, and the report was later criticized [152]. Finally, in 1972 a more reliable estimate of the quantity of O_2 showed 9.5 ± 0.6 cm·atm [54].

Observations by the Mariner 7 and 9 spacecraft in the polar areas of Mars indicated the presence of ozone O_3 (up to 57 μ·atm), appearing in late autumn, disappearing in early summer [133]. It was first assumed that it is absorbed on the solid surface of the winter polar cap. However, in 1971-72, ozone absorption was observed in the Hartley continuum (between 2000 and 3000 A) beginning at 30° north latitude, where there was no polar cap. The strong annual course of ozone is apparently related to changes in the content of water vapor [133]. Ozone is not observed in the equatorial regions. /67

In addition to what we have listed, no other components have been detected in the lower atmosphere of Mars; we can note only the upper limits of their possible content, below which they become undetectable [58, 81, 113]. It is theoretically probable that argon is present in relatively large quantities [39], although this question remains open, and current studies cannot yet answer it. If there is life on the planet, products of its metabolism may be present [93, 140]; however, attempts to find them on Mars have not yet been successful [107]. Further development of research methods is continuing [176].

Chemical-Dynamic Model of the Martian Atmosphere

In recent years, there have been some indications [114, 147] of a difficult contradiction between the low content of CO and O_2 in the Martian atmosphere on the one hand and contemporary theories on the other hand. Carbon monoxide is formed as a result of dissociation of CO_2 under the influence of solar UV radiation at $\lambda < 2270$ A, which penetrates to the lower atmosphere, and also under the influence of electron bombardment at the low energy of 11.5 eV. The reverse reaction does not occur. /68
Nevertheless, the low observed content of CO indicates that there must be a rather effective recombination reaction. We cannot as yet name any such reaction or, consequently, the conditions under which it might occur.

In the opinion of the authors of [148], the recombination of carbon monoxide to carbon dioxide occurs in the Martian atmosphere under the catalytic influence of water vapor. Therefore, the content of CO and O_2 in an atmosphere of CO_2 should vary as a function of water content and mixing intensity. The rates of the 15 basic reactions are presented in [148], and a model of the Martian atmosphere is constructed indicating the rates of recombination at various altitudes and the calculated concentrations of various components following from the model.

Thermal Mode

The surface of Mars, absorbing solar energy, reradiates it in the infrared range. The Martian atmosphere, when no dust clouds are present, transmits all solar radiation with $\lambda > 1900$ A freely, but absorbs the thermal radiation of the surface of the planet in the band around 15 μ and is thus heated. The diurnal temperature wave is propagated by radiant transfer from the base of the atmosphere to an altitude on the order of 1 km [103]. The time of thermal relaxation is significantly less than in the atmosphere of the Earth. Thus, the temperature of the lowest layer in the clear Martian atmosphere is determined by the temperature of the surface and may vary by more than 100° K during the course of the day.

Rasool and Stewart found that at local noon there is a 20-25° temperature drop between the warm surface of the planet and the cooler adjacent layer of the atmosphere [178]. However, their result may have been influenced to some extent by averaging /69 of the temperature over a comparatively thick lower layer of the atmosphere, which had not been heated by noon.

The amplitude of diurnal fluctuations in observed temperature decreases with altitude; in the clear atmosphere of an altitude of 10 km, the amplitude of fluctuations is 15° K [107], while in the dusty atmosphere it is significantly greater. The absolute temperature decreases with increasing altitude; inversions have been noted only in the night hemisphere [178], probably caused by extremely rapid cooling of the surface.

An extremely cold area has been found in the middle atmosphere of Mars, where CO_2 is present in saturation quantitites, and condensation might occur [178]. These results were produced by the radio refraction method in 1969. Measurements on Mariner 9 [127] also showed a temperature consistent with condensation of carbon dioxide near the morning terminator in the high latitudes of the winter hemisphere of Mars.

In the upper atmosphere, the mean temperature increases with increasing altitude, reaching 325-350° K at about 230 km [82, 207]. The temperature in the exosphere fluctuates widely. Analysis of the fluctuations indicates the influence of processes not directly related to solar activity [207].

Vertical Temperature Gradient and Dust in the Lower Atmosphere of Mars

We know that with subadiabatic vertical temperature gradient, stratification in the atmosphere is stable, while with superadiabiatic temperature gradient convection arises tending to reduce the gradient. In the clear atmosphere of Mars in the daytime, the observed rate of decrease of temperature with increasing altitude averages -2.3° K/km, i.e., is subadiabatic /70 [107, 128]. Nevertheless, there are probably some local factors causing temporary disruptions in stable stratification. Otherwise, it would be difficult to explain the mechanism of development of the currents which have carried dust to great altitudes. During the great dust storm of 1971-1972, in the daytime in the region of the equator the dust-containing layer of the atmosphere, some 10 km thick, was practically isothermal and, consequently, still more stable than with the subadiabatic gradient. Near the lower boundary of the dust-carrying layer (on the surface of Mars), the temperature was somewhat lower than usual, while at the diffuse upper boundary it was somewhat higher than usual for those altitudes, which is explained by the absorption of the sun's rays by the dust. The heating effect resulting from the presence of the dust was noticed up to at least 20 to 30 kilometers above the surface [127].

The vertical temperature gradient is a very sensitive criterion for clarity of the Martian atmosphere; it shows that dust may be present in the Martian atmosphere even when television images indicate that the atmosphere is clear.

According to the calculations of Ryan [184], the wind speed must be significantly higher than the observed speed of motion of the Martian clouds in order to raise dust from the surface of Mars. The dust clouds probably rise during squall-like gusts of wind, the velocity of which is significantly greater than the mean velocity, while the weaker circulation is sufficient to maintain the dust in its suspended state.

Winds and General Circulation

The dynamic and thermal structure of the lower atmosphere of Mars was studied theoretically by Gierasch and Goody [97] and by Golitsyn [11]. In both cases, a temperature jump was observed /71 in the lowest layer, about 10 m thick. In a layer about 1 km thick, in the opinion of the authors of these works, a free convection mode may obtain. Gierasch and Goody found that the primary component in the system of Martian winds is a seasonal zonal wind (i.e., directed practically along the parallels) with a mean velocity of about 40 $m \cdot sec^{-1}$. Golitsyn produced the following estimates of mean wind speed for an atmopsheric model with p_0 = 5 mb:$v \approx 20$ $m \cdot sec^{-1}$ at a height on the order of 10 m and $v \approx 40$ $m \cdot sec^{-1}$ at a height of about 200 m; with further increases in altitude, the wind speed changes more in direction than in modulus, and approaches geostrophic[8] at an altitude of 2 to 4 km. The total angle of rotation in the daytime falls within limits of a few degrees, while at night it may reach several tens of degrees. An estimate [12] of the wind speed in the Martian atmosphere based on the theory of similarity of large scale motions in the atmospheres of planets developed by Golitsyn yields 50 $m \cdot sec^{-1}$, i.e., a value similar to those produced by other methods.

Thus, theoretical estimates of the wind speed in the lower atmosphere of Mars yield figures of about 40 $m \cdot sec^{-1}$; however, they depend strongly on local relief and do not exclude the possibility of speeds exceeding 100 $m \cdot sec^{-1}$ [98].

Calculation of various versions of the model of general circulation in the Martian atmosphere has been performed by many authors. The results of numerical modeling of the atmospheric circulation of Mars performed by Leovy and Mintz [134] are quite interesting. The atmosphere was assumed to consist of CO_2; the transfer of solar and thermal radiation was considered. At the moment of the equinox, cyclones appear in the moderate and high latitudes of both hemispheres; in the middle latitudes, the winds are from the west, in the region of the equator -- from the east. During the season of the solstice, /72
east winds remain in the tropics, weaker in the summer hemisphere. In the winter hemisphere, the motions result from condensation of CO_2 in the polar cap: this causes meridianal transfer of gas across the equator, while cyclonic wave motions and strong west winds predominate in the middle and higher latitudes. In all cases, a diurnal tidal component is noted in the atmospheric circulation.

The field of winds (Figure 15), calculated in 1972 on the basis of Measurements of temperature in the atmosphere of Mars by Mariner 9, has confirmed the presence of both seasonal and strond diurnal winds [107], as found earlier by Goody and Belton [103], Leovy and Mintz [134] and others.

Miyamoto attempted to produce information on the dynamics of the Martian atmosphere directly from observations [153]. Usually, visible displacements of cloud systems relative to the physical surface of the planet are used to estimate wind speeds in the lower atmosphere of Mars by terrestrial telescopic observation. The observation of yellow (probably dust) clouds indicates speeds of about 15 $m \cdot sec^{-1}$. In the case of white clouds, it is apparently not always possible to identify wind speeds and the speeds of movement of bright spots on Mars. One of the authors of this chapter (Davydov) has repeatedly encountered records of observations of white spots moving at almost the speed of sound for many hours in the memoirs of well-known observers of Mars. Apparently, in some cases what was observed was not the mechanical motion of an object, but rather optical displacement of conditions of condensation, or conditions of visibility of a bright spot. However, this possibility forces us to approach the more acceptable estimates of wind speeds on Mars made by the same method with caution as well.

Miyamoto found [153] that in late spring in the southern hemisphere the direction of the seasonal wind changes from west to east. This season is usually accompanied by the appearance of a global haze and a halt in the retreat of the boundaries of the polar cap. Miyamoto notes examples of the influence of topography on atmospheric circulation. /73

The mode of the general circulation, according to Miyamoto, is near symmetrical, whereas Tang [209] concluded that such a mode would not be stable on Mars, and that rather a wave mode should predominate.

Luminescence of the Upper Atmosphere and Parameters of the Ionosphere

Hard solar radiation causes ultraviolet luminescence of the upper atmosphere of Mars, brightest in the Cameroon bands of CO (λ 1900-2700 A, up to 300 kR) [207]. Other bright emissions have been observed by the Mariner 6, 7 and 9 [56, 206] (Figure 16) and Mars 2 and 3 [82] spacecraft.

The data of on-board and terrestrial spectrometry, in combination with radio occultation measurements, have served as a basis for construction of a model of the composition and structure of the ionosphere and upper atmosphere of Mars [57] in the altitude range from 100 to 230 km, i.e., practically up to the lower boundary of the exosphere. The most important component of the martian ionosphere, according to UV spectrometry performed by Mariner 9, is nothing other than O_2^+, while CO_2^+ is a secondary component. OI and HI are also present, at relative concentrations at the 135 km level of 10^{-2} and 10^{-6} respectively [57].

The results of radio occultation experiments by Mars 2 and Mariner 9 [22, 127] confirm the existence and refine the parameters of the Martian atmosphere, observed earlier by Mariner 4, 6 and 7 flyby spacecraft. At 134-140 km from the surface of Mars, with zenith scattering of the sun at about 50°, the electron concentration is $(1.5\text{-}1.7)\cdot 10^5$ el$\cdot$cm^{-3}, which correlates with the flux of short wave solar radiation measured on the Earth. Furthermore, it is reported in [22] that observations by Mars 2 determined a second maximum at an altitude of 110 km with a concentration of $7\cdot 10^4$ el$\cdot$cm^3. /74

The Surface of Mars

Temperature of the Surface of the Planet and Nature of the Polar Caps

The indicator of temperature is the intensity of natural thermal radiation of the surface in areas of the spectrum where reflected solar radiation can be ignored. Measurements have been performed both from terrestrial observatories and from spacecraft in the range of 8 to 40 μ. The absolute temperature thus determined must be corrected for the radiation factor; refinement of this factor requires that we know the mineral composition of the surface of Mars.

The results of terrestrial measurements are clearly illustrated by Figure 17, borrowed from [159]. The preliminary results of measurements from Mariner 9 and Mars 3, published in [107] and [42-A] (Figure 18) refine and increase the detail of the information, without making any basic changes.

From the point of view of inhabitants of the moderate climatic belts of the Earth, it is very cold on Mars. Even in the tropics, there is a hard freeze each night, and the sun's rays heat the surface above the freezing point only during the day. The maximum temperature is observed just after noon, reaching in some areas 300-305° K; by evening (but still two hours before sundown), the surface cools to the point that frost /75
is formed, and at night the temperature drops below (possibly far below) 200° K. This is near the equator. The sharp diurnal variations in surface temperature are attenuated beneath the outer layer of matter; at a depth of a few dozen centimeters they are practically nil.

The mean temperature over the entire day is below freezing everywhere, with the possible exception of some individual areas where the liberation of internal heat of the planet is high. In the polar zones, as would be expected, it is significantly colder than in the tropical belt; in the winter time, temperatures of around 150° K have been recorded here. This value is near the point of condensation of CO_2 under the conditions on Mars. This indicates the possibility that it may snow dry ice on Mars. The solidification point of dry ice on the surface of the Earth is 195° K, but depends on pressure, so that on Mars, with a pressure of about 5 mb, it is about 150° K.

In the winter hemisphere of the planet, a white spot around the pole can be clearly seen through a telescope. The visible portion of this polar cap on Mars is only found in the coldest daytime regions, bordering the area of polar night. A few months pass; in the spring and early summer, the white cap decreases rapidly in size, but another appears at the opposite pole, where winter is beginning. The process of fall and winter growth of the polar cap is usually obscured by a continuous layer of clouds, which arises at this time over the polar area.

The north polar cap is not as large as the south polar cap, which has a mean diameter by midwinter of 3500 km, in some cases reaching over 5000 km. However, the huge south polar cap almost completely disappears during spring and summer whereas the north polar cap shrinks more slowly and its remainder (varying from year to year) is always over 350 km in diameter.

In the late 19th and early 20th century it was assumed that /76 the polar caps of Mars consisted of ice and snow, the spring thaw of which was the main source of moisture for the hypothetical Martian biosphere. However, after spectroscopic observations showed the paucity of water vapor in the Martian atmosphere, the opinion concerning the white polar cover changed: it was assumed to be a thin layer of water frost. The results of spectrophotometry indicated that ice crystals were present.

Still more recent data have resulted in a basic change in the classical concept of the nature of the polar caps on Mars.

Mathematical modeling, followed by the significant improvements in the spatial resolving capacity of instruments used for radiometric measurements of the surface temperature of Mars, in combination with the results of spectrometry, showed that carbon dioxide is included in the composition of the white polar cover. At the same time, there are several characteristics indicating the presence of ice. One of these is the existence of the remainders of the northern (and sometimes southern) polar caps during the Martian summer. The rate of evaporation of dry ice under the conditions of polar day on Mars is so great that a dry ice polar cap formed during winter could not be conserved, even at the pole. However, the rate of evaporation of ordinary ice into the Martian atmosphere is so slight that water ice might survive.

In the opinion of some specialists, the heart of the polar cap is made of ice, which may be covered by solid carbon dioxide during the winter. The presence of carbon dioxide clathrates is probable.

During the spring and summer reduction of the size of the /77 polar cap, a dark border several hundreds of kilometers wide is observed around it; the reality of the dark border has been confirmed by photographs of Mariner 9. Some specialists have thought that the dark border results from an increase in moisture in the soil due to thawing of glaciers. However, this connection could only be indirect, not direct, since the temperature of the horizontal surface at this point is below freezing, with only slopes turned toward the sun rising above the freezing point. Sagan and his colleagues have suggested a hypothesis [192] for the development of the dark border: they indicate the possibility of blowing of light dust away from the dark soil by the winds which are caused by the difference in temperature between the polar cap and its surroundings.

The Heat-Physical Properties and Mineral Composition of the Surface of Mars

the outer cover of Mars (at least over a significant portion of the surface) consists of highly dispersed matter. This is confirmed by the formation of the dust clouds, by terrestrial polarimetric observations and by comparison of the daily course of temperature of the surface with the insolation conditions. The fluctuations in temperature, both as to amplitude and as to phase, correspond to a thermal inertia factor $(k\rho s)^{1/2} < 0.01$ $cal \cdot cm^{-2} \cdot sec^{-1/2} \cdot {}^\circ K^{-1}$ [39, 200]. The symbols are explained in the section on Mercury. This thermal inertia, characteristic for sandy soil, is much less than that of solid rock. Careful and repeated analysis of the observations of Sinton and Strong was performed by Morrison [156]. The thermal inertia of the soil of the planet as a whole was found to be 0.005, of the equatorial belt 0.01; these figures indicated mean particle diameters of 100 and 25 μ respectively.

Meteorite material should have enriched the outer cover of Mars with iron. Some feel that the reddish color of the surface /78 of the planet results from the presence of at least an admixture of hydrated oxides of iron. Ocherous limonite was first named [48, 91]. It was demonstrated in [45] that hematite or goerthite, but not limonite, could be formed under the conditions present. The results of Sinton contradict the "limonite" hypothesis; only a slight percentage content of iron oxide could be present [199].

According to infrared spectroscopy performed by Mariner 9, the dust raised from the surface of Mars into the atmosphere contained 60 ± 10% SiO_2 [107], i.e., approximately the same as in the sand of deserts on the Earth [43]. There are indications that SiO_2 is present in the surface layer of Mars as well.

Surface Albedo. Properties of Light and Dark Areas in Relation to the Problem of Biological Activity on Mars

The monochromatic geometric albedo of the full disc of Mars in the visual area of the spectrum rises steeply from 0.05 in the violet to 0.25 in the red area, reaching its maximum of 0.30 around $\lambda = 0.8$ μ, then falling off slowly with further increases in wavelength of reflected radiation [39].

The reflective properties of various sectors on the surface of Mars differ. For one of the lightest areas, Arabia, the maximum geometric albedo is 0.43, three times higher than for the dark area Syrtis Major [144].

On maps of Mars based on surface telescopic observations, the light areas occupy some 2/3 of the surface of the planet. /79
These are the so-called continents. Not over 1/3 of the surface is covered with dark areas, earlier given the Latin names of seas, bays, lakes and swamps, borrowed from geography and ancient Greek mythology. There is no need to explain that a classification consisting of bodies of water and continents is arbitrary, as is true for the lunar "seas" which contain no water.

The spectral reflective capacity of the light areas and yellow clouds have been found to be similar. On this basis, it is believed that the light areas are covered with a layer of fine powder, which is easily raised by the wind. However, one must consider that the albedo of clouds of fine particles might be higher than the albedo of a surface made of the same material.

Concerning the nature of the dark areas, there is no single opinion. Since the publication of a book by P. Lowell [141] containing the alluring but falsely based hypothesis of the possible artificial origin of the Martian "canals," the idea of the probable relationship of the dark areas to biological activity on Mars has been discussed in various versions. Proponents of this idea base their arguments on the obvious fact that a covering of plant-like organisms should be rather dark, since plants utilize the energy of solar rays and, furthermore, can make shade. The properties of the Martian dark areas, which are difficult to explain, are frequently among the arguments set forth in favor of the hypothesis of existence of a Martian biosphere. For example, it has been reported that the dark areas which disappear in the yellow haze during dust storms reappear in the same places as the atmosphere clears. The question is, why are they not covered by a layer of the light material which falls to the surface as the dust storm dies? Furthermore, it has /80
been established in recent years that the outlines of the classical shaded areas in many cases have no relationship to the boundaries of different relief forms [80]. However, the most important argument is the long-discussed variability of the dark areas. Many works have been dedicated to as yet rather fruitless discussion of the causes of their curious behavior, significantly fewer works -- to careful and qualified observation of the properties of variability. Of what does it consist?

According to terrestrial telescopic observations, as is noted in [50], "The outlines of the dark areas are stable on the average, but in some places they change quite strongly in intensity and extent. The reality of these changes, doubted by Secci, was established by Flammarion; in some cases, the changes are secular in nature, but they may be seasonal as well."

Antoniadi presents examples of changes of various types. He indicates that the broad, most clearly visible dark area, Syrtis Major, undergoes seasonal changes. However, in our opinion, this effect may be related to the selectivity of the observations, since the season of expansion of this detail correlates with increasing distance to Mars and an increase in the minimum linear dimensions of parts studied near the threshold of angular resolution.

New facts concerning the secular and irregular changes were determined by de Mottoni on the basis of extensive observational material [160]. We should note here that in most cases it is possible only to speak of changes in the contrast of a given area with the surrounding background. Furthermore, Dollfus noted seasonal changes in polarization of both dark and light areas. In spring and early summer, an anomalous negative polarization is observed [86].

As concerns the problem of the dark areas of Mars, it is /81 unfortunately not always possible to separate solidly known facts from insufficiently confirmed opinions. Following the great opposition of 1909, a report on a seasonal "wave of darkening" of the dark details on the surface of Mars was widely published. Scientists, assuming the possibility of the existence of life on Mars, noted the external similarity of the Martian "wave of darkening" to the annual development of oases of vegetation. Due to its great repetition in the popular scientific literature over many years, the Martian "wave of darkening" became so popular, that it began to be treated as a well-known fact. However, this is not quite correct. A recent attempt by V. D. Davydov to determine the peculiarities of the seasonal course of the "wave of darkening" on the basis of 200 of the best available terrestrial photographs from among those published by various authors and covering the interval from 1907 to 1971, to the great surprise of the author, showed no such clear seasonal change. Apparently, the question not only of the causes, but even of the basic properties (including the regularity) of changes in the optical characteristics of the dark areas must be considered insufficiently studied. Long series of spectrometric observations excluding optical illusions based on physiological properties of vision are required here. However, even the replacement of the eye with the instrument cannot exclude the influence of variability of the quality of the telescope image, which depends so strongly on the turbulent motion of the air over the path of the beam through the atmosphere of the Earth.

McCord and Westphal performed terrestrial spectrometric comparison of dark and light areas of Mars in the spectral band from 0.3 to 2.5 μ [144]. In two months, the light area became brighter and redder, whereas the dark area remained as before. /82 The changes determined differ from those which might be caused by the traditional "wave of darkening." However, even after determining the falseness of our concept of the "wave of darkening," the nature of the dark areas remains puzzling and requires careful study.

Throughout the entire time when attempts to compare the optical characteristics of the dark areas on Mars to the optical properties of terrestrial vegetation and organic substances were undertaken [46, 198] and discussed [179, 208], a parallel search was undertaken for an abiogenic mechanism for the changes in the dark areas. Many different explanations were suggested, and are briefly discussed in review [39]. For example, Cohen [70] relates the color of the dark areas and the yellow clouds to the coloration of the products of chemical interactions between Fe and CO: $Fe(CO)_5$ is yellow, $Fe_2(CO)_9$ is orange, $Fe_3(CO)_{12}$ is green.

Using the criterion of greatest acceptance in recent years, we can differentiate one group of similar hypotheses relating the variable properties of the surface of the dark areas to processes of weathering and wind transfer of crushed material. According to Sharonov [194], the light products of weathering are periodically carried away by trade winds. In summer, the dark surface is uncovered, which might serve as a reason for the anomalous polarization. Sagan and Pollak have developed a hypothesis concerning changes in dimensions of particles on the surface of certain areas of Mars under the influence of seasonal variations in wind mode [189]. The irregular changes in the dark spots are explained by Pollak and Sagan by blowing of the light dust away from the dark surface -- cf. the hypothesis of Sharonov, in which the same method was used to explain the regular changes. These models are based on the conclusion that the /83 dark areas are elevated, the light areas -- lower in elevation. However, radar has failed to confirm the existence of either this or the reverse regularity.

In 1972, a new modification of an old idea developed: probably, the visibility of the dark areas on Mars changes only as a result of changes in dustiness or transparency of the Martian atmosphere due to local seasonal variations in wind speed. This is an interesting thought, but does not provide a final solution to the problem, since variations in transparency alone cannot explain the occasional appearance of new dark areas, not observed before.

New information, bringing us closer to an understanding of the nature of the dark areas, was produced as a result of the television picture of Mars taken by Mariner 9. The large dark area Syrtis Major, on photographs taken from an altitude of less than 2000 km, was found to consist of a number of dark "plumose" spots, as well as light and dark bands which extend for tens, sometimes hundreds of kilometers with no topographic relief, even in photographs with the best angular resolution [142, 191]. The light bands are longer and narrower than the dark bands. Both generally originate in craters or projecting relief details, indicating that the bands originate with winds which blow in stable directions.

One photograph taken from Mariner 9 shows a large-plan image of a dark spot, covering a portion of the crater floor within a circular wave. The figure (Figure 19) shows that the dark area is covered with details of identical orientation, similar to the dunes formed by winds of stable direction. The dark spots detected in certain other craters probably are of the same nature. However, there is no reason to assume that all varieties /84 of dark spots on Mars without exception are dune fields. Sagan and his colleagues [192] assume that in many cases the dark surface areas are outcroppings of solid rock in areas covered with light powder ash. Furthermore, they assume the existence on Mars of both light and dark mobile material.

A comparison of the same spots on photographs made at different times has allowed American specialists to determine changes in the albedo of individual sectors in comparison to the albedo of neighboring areas within the field of vision. The characteristic time of changes is not over 2 weeks. The appearance of new or disappearance of old bright bands was not observed.

From the point of view of the reader, looking over the published photographs, the most noticeable changes consist of increases in area due to movement of boundaries of the dark spot, with conservation of all details of the fine structure unchanged within the limits of the previous boundaries. Sagan and his colleagues defend the wind-dust genesis of the spots and bands and of their changes with time [191]. These same researchers assume that local changes in spots and bands cause the classical seasonal and secular changes in albedo of the Martian dark areas.

The parallelism of the "tails" of certain groups of craters form a convincing argument in favor of the influence of wind deposits on the surface albedo. However, we cannot be completely sure that the wind-dust mechanism of these changes is universal and unique for different types of details. Biological activity /85 is apparently not excluded by any of the contemporary data, although we must note that the old arguments in favor of its existence can no longer be used.

The Question of the Martian "Canals"

We can now state with assurance that the series of lines of unusually straight geometric form observed on Mars are the result of a complex and insufficiently studied optical illusion arising not only during visual observations, but even during photography of Mars through weak telescopes or with poor image quality.

The photographs made by spacecraft show no network of "canals" on Mars. Nevertheless, some quasilinear natural formations are present. Among these, however, the large ones are not sufficiently regular, the small ones could not possibly be seen under any conditions from Earth.

The Relief of Mars

A Few Words on Methods of Altitude Measurement

It was quite recently assumed that the surface of Mars was mostly smooth and, possibly, quite free of slopes. No mountain shadows could be observed through telescopes; the lines of the twilight band between the day and night hemispheres of the planet were smooth, without dark projections. The estimates of the upper limit of altitude of Martian mountains with sharp shadows, which might remain unseen from the Earth, have been found to be too rough. This is probably a result of difficulties in accounting for atmospheric interference. New methods have come to the aid of astronomers. Radar observations of Mars from the surface /86 of the Earth allow us to measure the distance to the subradar point (at the center of the visible disc of the planet) with extremely high accuracy (down to ±75 m) on the basis of the delay time of the radio echo. The axial rotation of Mars causes the subradar point to shift along a single parallel. Continued operation of the radar set yields a profile of the surface of the planet along the subradar parallel. As time passes, the areographic latitude of the subradar point changes slowly; in this way, radar profiles of the Martian relief have been made along several parallels [90, 168].

Unfortunately, radar cannot in principle compare the height of levels at points far from each other on Mars. It yields only the altitude measured from the level of a sphere, the center of which corresponds to the center of mass of the planet. Also, any surface of equal altitudes (i.e., any gravitationally equipotential surface), from which the heights of mountains and the depths of depressions on Mars could be measured, will hardly be precisely spherical, but rather will be quite complex in form, deviating from the approximation of a sphere in points by up to 10 km. Comparisons of heights of details on the radar profile can be made without knowing the shape of the surface of equal altitudes only over a comparatively short sector.

Other methods, based on measurement of the gas content above the surface of Mars in a vertical column of unit cross section, can be used to relate all measured levels to a single common level for the entire planet. Obviously, there is more gas above a depression than above an elevated area. By comparing the atmospheric pressure over two different points, then using the known barometric formula, we can find the difference in levels (or difference in altitudes) of the solid surface of the planet at the points observed. The surface heights produced by the barometric formula are called barometric altitudes (or pressure /87 altitudes), the method is called barometric hypsometry.

The pressure at the surface (and, consequently, barometric altitude) can be found by at least 3 methods: first of all, by means of spectrometry based on the peculiarities of spectral lines; secondly, by the scattering of light in the atmosphere; and, thirdly, by the radio refraction method using spacecraft. On-board hypsometry using all of these methods on the Mariner 6, 7 and 9 spacecraft, as well as spectral hypsometry from terrestrial observatories and the Mars 3 spacecraft have yielded extensive material, based on which preliminary maps of altitudes of the surface of Mars have been composed [74, 112, 128].

What can be used as the zero altitude level on a planet which does not have such a convenient bench mark as "sea level"?

The origin of the reading has been taken as the 6.1 mb barometric pressure level -- the triple point of H_2O, corresponding to a reduction in boiling point of water to 0° C. Above this altitude level (i.e., at lower atmospheric pressures), H_2O can exist only as ice or steam, whereas below this level it can exist as a liquid. We will present below a few interesting results of measurement of barometric altitudes.

Unfortunately, measurements of barometric altitude may contain significant errors, resulting from variations in atmospheric pressure of seasonal [75], diurnal [74] and meteorological [117] nature, as well as a few unavoidable simplifications in the theory. The results produced at different moments in time do not belong to the same system of reference, since the zero level altitudes drift, and the scale of altitudes does not remain /88 strictly constant.

At present, it is impossible to correct for many of these sources of error. Nevertheless, the method of measurement of barometric altitudes by measurement of atmospheric pressure both in the optical band (with preference to the long wave region of the spectrum, where aerosols have less influence) and in the radio frequency band continues to be the only method for comparison of altitudes of surface level at distant points on the planet and production of such important relief characteristics as the full amplitude of altitudes.

A Review of "Geological" Forms on Mars

The preliminary results of geological studies [142], based on the results of television experiments conducted by Mariner 9 in 1971-72, indicate that the surface of Mars is a result of a more complex geological history than that of the moon. Mars photographs show traces both of meteorite impacts and of volcanic and tectonic activity, traces of many processes of surface erosion, movement and deposition of sediment.

Following basically report [142] and supplementing it somewhat by reports from other works, let us briefly characterize the main types of Martian relief.

Territories Covered with Craters

Such territories are quite extensive on Mars, but are not the dominant type of surface, in contrast to the opinion formulated after the first Mars photographs were returned by spacecraft. The morphology of craters and distribution by dimensions indicate that most of them are of meteorite origin. Possibly, a /89 few are of volcanic origin, but such craters are difficult to distinguish from meteorite craters when both have been greatly altered.

Mountainous territory. One example is the area from 260 to 310° west longitude along the 20th parallel in the southern hemisphere of Mars. Multiple-peaked, primarily smoothed mountains, similar to the Apennine chain on the moon. We also encounter volcanic mountains on Mars, as well as high slopes of fault origin and waves of impact-explosive origin. Smooth planes are located around the higher relief forms. They occupy a significant portion of the northern hemisphere, as well as the surface of the large basins in the central southern latitudes and the floors of some large craters. This relief form possibly has several varieties and is distinguished by one characteristic peculiarity: few or no craters.

Volcanoes. In the lower northern latitudes from 90 to 140° and around 210° west longitude (in the areas of Tharsis-Amazonis-Elysium) there are many volcanic domes. Among them are four gigantic volcanic shields, the larges of which (in volume) is in

the area of Nix Olympica [18°, 134°). Above it rises a huge volcanic cone. The caldera at its peak consists of several adjacent craters with floors at different levels (Figure 20). The main crater, 65 km in diameter, is located at an altitude of over 10 km over the surrounding terrain. The foot of the mountain consists of dark material and is separated from the surrounding plain by steep cliffs. The diameter of the base is around 500 km. Nix Olympica is significantly larger than the /90
world's largest volcanic formation, 225 km in diameter, in the Hawaiian Islands, with its main crater Mauna Loa at an altitude of over 4000 m above sea level and 9 km over the plain of the ocean floor.

Not far from Nix Olympica is the highest of the Martian peaks. It belongs to a volcano located at the center of a great dark spot, the middle spot (0°, 112°). The crater of the volcano rises 13.5 km above the level of the foot of the mountain, 19.2 km above the arbitrary zero level and more than 23 km above the level of the lowest plains [107]. This crater, 40 km in diameter, has been photographed in large scale (Figure 21). The photograph clearly shows vertical traces of slides and small meteorite funnels on the inner slope of the circular wave. The bottom is flat and smooth.

Around the volcanoes are many structures indicating an era of widespread volcanic activity after completion of the process of formation of the territory covered by the meteorite impact craters. A volcanic formation of a quite different type has been found in Mare Tyrrhenum, around -22°, 253°.

The spectral search for volcanic gas, particularly water vapor, made by Mariner 9 in the calderas of Martian volcanoes yielded no positive results. During the final stage of the life of Mariner 9, the infrared instruments indicated water clouds in one crater.

Grabens[9] and the Grand Canyon. Some territories are cut by a network of wide, deep grabens -- traces of fractures and faults.

The largest of the Martian grabens is the Grand (or Main) /91
Canyon, which extends for 2500 km in the region of Tithonius Lacus-Coprates-Aurorae Sinus-Eos. It is 100-250 km wide. In the area of Melas Lacus, the canyon is bordered by two trenches, the total width reaching 500 km. The slopes are cut by giant ravines (Figure 22). Along the Grand Canyon, the photographs show chains of craters with no waves. They seem to be strung along the great crack.

The depth of the Grand Canyon from the level of its edges is in places 6 km. The complexity of the problem of removal of rock from the canyon system was noted in [142]. Some of the material might have been carried along the canyon in the direction of the slope, from west to east. However, no details indicating such transfer have been discovered. Furthermore: on the north side of the canyon system we can see a broad, deep, fully closed basin. This is consequently either a result of settling or the material was removed by the wind.

Chaotic territories are encountered on Mars in the form of large, isolated spots. They have no known analogues on the Earth or on the moon. They contain blocks of rock intricately broken and split. The form is explained by settling of the outer layers following removal of material from beneath the surface.

Circular basins: Reminescent of giant craters, they have flat bottoms and are surrounded by mountain areas. Formations of this type include, for example, Libya, Edom, Iapygia.

The greatest Martian basin is Hellas, some 1500 km in diameter. This is a depression, some 4 km below the 6.1 mb barometric pressure level. /92 The surface of Hellas is smooth, with no craters or other relief details. The reasons for the absence of traces of meteorite impact, which have severely bombarded neighboring areas, are not clear. Several different hypotheses have been set forth to explain the observed peculiarities of Hellas. Some specialists assume that clouds of dust exist here constantly [190], covering the true relief. The author of another hypothesis [15], assumes that within Hellas there is a great water basin, covered with a solid layer of frost and wind sediment with a comparatively young outer surface. In this model, only small funnels could be formed, the dimensions of which are small in comparison to the thickness of the solid crust on the surface of the water. A larger meteorite impact would cause a penetrating hole, which would be immediately filled with water to the Archimedes level, covered rapidly with ice and in time "powdered" with dust.

Stream-like formations. According to current concepts, rivers could not flow on Mars at present: the mean daily surface temperature is below freezing in all climatic zones. Furthermore, due to the low atmospheric pressure, H_2O can exist only as ice or steam over the entire surface of Mars, except for depressions. Therefore, the discovery of channels, quite similar to river beds on the Earth, on the photographs of Mariner 9, was quite surprising (Figure 23).

A broad, winding valley with "tributaries"; typical shore line terraces, stream bed sediments, islands with their characterstic outlines are all visible. In places in the valley we can see a dark "thread" several kilometers wide, i.e., hardly a Volga /93 or Mississippi: probably traces of a stream bed. Around all this, a typical Martian scene: the ancient surface, broken over the centuries by young and old craters.

Several stream-like formations on Mars extend as much as 1500 km in length, over 200 km in width. This is reality, and it requires an explanation which does not contradict other firmly established facts. To cut these stream beds would require a tremendous quantity of water or some other liquid. It was noted in [142] that, in addition to a stream of liquid, one must analyze the possibility of erosion by a fluidized "solid-gas" system. The authors of this work assume that the source of the liquid was more probably the lithosphere than the atmopshere. This is indicated by the fact that some of the largest stream beds are to be found in the chaotic territory. In areas of elevated geothermal flow, the subsoil ice is probably thawed. The liquified material accumulates in a natural impermeable reservoir until it bursts. Then, a brief but powerful flow develops. However, the authors of [142] conclude, this idea requires further development.

In some cases, small streams are encountered in areas where the presence of ice beneath the surface is impossible, for example within meteorite craters on the slopes of the central peaks. In this type of situation, water erosion would require intensive precipitation of H_2O from the atmosphere.

In the current era, there is no rain on Mars. This fact follows from all available physical parameters of the lower atmosphere and is confirmed by the absence of the 41° (corresponding to a water-drop rainbow) maximum in the distribution of phase /94
angles of short-lived bright formations [14, 16].

Could there have been rainy weather on Mars during some past period of its history? The possibility of this event has been a subject of discussion of planetary scientists since long before the discovery of the Martian stream beds. The precession of the axis of diurnal rotation of the planet and rotation of the orbit in its plane give us reason to believe that from time to time on Mars, eras of increased atmospheric pressure and milder temperature conditions than at present could exist. As we have already stated in the section on the peculiarities of the seasons of the year, the passage of Mars through the perihelion softens the climate of one of its hemispheres. The slow "drift" of the date of the perihelion over the entire Martian calendar means that during some eras the climate of the northern hemisphere is milder, during other eras -- the climate of the southern hemisphere. It has been assumed that there are periods in this cycle when the total mass of the two polar caps is minimal. Then, the evaporation of the polar reserves of solid carbon dioxide leads to the delivery of a large quantity of carbon dioxide gas to the atmosphere, to an increase in atmospheric density. During these eras, bodies of water could apparently exist on Mars with open liquid surfaces, maintained by the reinforced greenhouse effect. However, as yet this is only a hypothesis, since the possible amplitude of variations of atmospheric pressure is unknown.

Polar relief. Original surface forms are encountered in the areas covered in winter by the polar caps. Even after the white cover retreats, the surface seems to be covered by multiple layers of precipitation. These deposits give the impression of comparatively smooth polar relief, approximately the same winter and summer, apparently replacing the depressions and covering the other varieties of geological structures observed in the /95 lower latitudes.

The Problem of Water on the Planet

According to the results of spectral measurements, the absolute content of water vapor in the Martial atmosphere is very low (see section on chemical composition of the atmosphere). However, in some places during certain seasons, the <u>relative</u> humidity reaches 100%. We know from physics that the absolute quantity of water vapor in the atmosphere is limited by temperature, and at low temperatures saturation occurs at extremely low absolute humidity. For this reason, the low content of moisture above the Martian surface cannot be taken as a reliable indication of a shortage of water resources. Let us recall that here on Earth the water reserves are significantly greater than its content in the air. How much water may be concentrated in the outer layers of Mars we simply do not know, and do not have sufficient basis to consider the reserves slight. This point of view is favored by theoretical constructions based on the firmly established fact of the existence of volcanoes on Mars. From the point of view of contemporary geophysics, when the rock of which volcanic domes are formed was ejected from the bowels of Mars, significant quantities of water should have been liberated.

At present, most of the reserves of water on Mars may be concentrated in the layers of sediment in the form of permafrost [26] or, possibly, even in large bodies of water beneath a layer of permafrost [13], where the ordinary geothermal gradient would produce positive temperatures.

Certain peculiarities which have been observed might indicate significant reserves of water in the outer layers of Mars: /96

a) the stream-like formations;

b) indications of the existence of glaciers in the polar caps;

c) the presence of large basins, at least one of which has a completely smooth, quite level low surface.

Phobos and Deimos.

The natural satellites of Mars were discovered visually by A. Hall in the telescope of the U. S. Naval Observatory in 1877, and first photographed at the Pulkovo Observatory in 1896. They differ from the known satellites of all other planets in their extremely low altitude and small dimensions.

The information produced by terrestrial methods can be reduced primarily to determination and refinement of the parameters of orbital motion of Phobos and Deimos [196]. They revolve around Mars almost in the plane of the equator. Phobos flies over the Martian surface 70 times closer than the moon to the Earth and makes a full orbital revolution each 7 hours 39 minutes (siderial period), i.e., more rapidly than the diurnal rotation of the planet. This is the only known case of this phenomenon in the solar system.

The unique photographs of the satellites of Mars made by Mariner 9 [174] show that they are small, natural bodies; that they are not spherical, and in shape are more reminescent of potatoes (Figure 24). Phobos measures approximately 21 x 26 km, Deimos -- 12 x 13 1/2 km. They both have the same albedo as basalts and carbonaceous chondrites. Of the relatively dark /97
minerals, these two are the most abundant in the solar system. However, we cannot make a selection between them [174].

The surfaces of the satellites of Mars show many craters, definitely of impact origin, since it is fundamentally impossible for centers of volcanism to exist within such tiny bodies. The larges crater on Phobos is 5.3 km in diameter. The power of an impact capable of forming such a crater is near the power necessary to destroy this satellite entirely.

The number of craters per unit surface area of Phobos and Deimos is approximately 100 times that of the surface of Mars. This indicates the effectiveness of the processes which smooth the relief on the surface of the planet, and the great age of its satellites.

Judging from the synchronism of the periods of axial rotation and of orbital rotation around the planet currently achieved, the last impact of a sizable meteorite on Phobos occurred more than 10^6 years ago, on Deimos -- 10^8 years ago.

Once More Concerning the Problem of Life on Mars

Up to the present, we have not produced sufficient information to prove the existence of biological activity on Mars. Whether the firmly established facts include any which could reliably eliminate this possibility must be judged not by astronomers but by biologists. The new information on Mars produced in 1971-1972 apparently has provided a foundation for undertaking further studies to solve this problem. These efforts will be undertaken, and there is hope that the completion of this theme of study will serve as a beginning for many other studies.

Conclusions /98

Many problems related to the planets of the Earth group still await their solution and are being solved at the present time by the combined efforts of astronomers and space scientists. The further growth of our knowledge in this area will not only help us to better understand the nature of our neighbors, but will bring us closer to the solution of a number of geophysical problems, and thus broaden the prospects for achievement of results for the good of all mankind.

[Two signatures]
24 September 1973

TABLE 1

GEOMETRIC, SPIN AND MASS CHARACTERISTICS
OF PLANETS OF THE EARTH GROUP

Planet	Equatorial Half Diameter		Geometric Polar Compression	Inclination of Plane of Equator to Planet of Orbit	Direction of Axial Rotation
	Linear, km	Maximum Angular			
Mercury	≈2450	≈6.3"	?	<3°	Direct
Venus	6050± ±5	31.9"	Not detected	<3°	Reverse
Earth	6378	--	1/296	23°27'	Direct
Mars	3397± ±3	12.5"	≈0.0051	25.0° ± ±0.3°	Direct

*In units of mean solar days of universal time.

TABLE 1 (Right Side)

Length of Stellar Day	Mean Solar Day	# of Solar Days Per Orbital Revolution	Mass of Planet in Units of Earth Mass	Mean Density, g/cm^3	g at Equator, cm/sec^2	Critical Velocity, km/sec
58.65*	175.9*	0.500	0.05526± ±0.0048	5.38± ±0.08	≃ 370	≃ 4.3
243.0*	116.8*	1.924	0.8150	4.86	876	10.2
23 hr, 56 m, 1 s	24 hr, 0 m, 0 s	365 1/4	1.0000 (without moon)	5.52	981	11.2
24 hr, 37 m, 22.7 s	24 hr, 39 m, 35 s	668 2/3	0.10744± ±0.00003	3.94	371	5.0

TABLE 2

MEAN ORBITAL ELEMENTS OF PLANETS OF THE EARTH GROUP IN SYSTEM OF COORDINATES WITH ECLIPTIC AND POINT OF VERNAL EQUINOX OF EARTH IN EPOCH 1950.0

Planet	Mean Distance from Sun		Rotation Period*		Eccentricity	Inclination
	Millions of km	a.u.	Sidereal	Mean Synodic		
Mercury	57.91	0.38710	87.97	115.88	0.2056	7°1'14"
Venus	108.21	0.72333	224.70	583.92	0.0068	3°23'39"
Earth	149.60	1.00000	365.26	--	0.0167	--
Mars	227.94	1.5237	686.98	779.94	0.0934	1°51'0"

*In units of mean solar days of universal time.

TABLE 2 (Right Side)

Longitude of Ascending Node	Annual Change	Longitude of Perihelion	Annual Change	Mean Longitude of Planet in Initial Epoch	Mean Velocity of Motion in Orbit, km/sec	Mean Angular Velocity of Motion in Orbit per Day
47°44'19"	+0.71"	76°40'39"	+0.93"	33°10'6"	47.83	4°5'32"
76 13 39	+0.54	130 52 3	+0.84	81 34 19	34.99	1°56'8"
--	--	102 4 50	+1.03	99 35 18	29.76	0 59 8
49 10 19	+0.46	335 8 19	+1.10	144 20 7	24.11	0 31 27

TABLE 3

CHEMICAL COMPOSITION OF THE ATMOSPHERE OF VENUS AND UPPER LIMITS OF CONTENT OF POSSIBLE IMPURITIES

Component	Relative Content	Method of Determination	References	Note
CO_2	$0.97^{+0.03}_{-0.04}$	Venera 4.5.6	[9]	
N_2 (Including Inert Gasses)	2.10^{-2}	"	"	
H_2O	$(0.6-1.1)\cdot 10^{-2}$	"	"	Where $P = 2-0.6$ kg/cm^2
H_2O	$(0.4-2)\cdot 10^{-3}$	Radio Astronomy	[120]	
H_2O	$\approx 7.10^{-5}$	Spectroscopy	[131]	
O_2	$<10^{-3}$	Venera 5.6	[9]	
O_2	$<10^{-5}$	Spectroscopy	[60]	
CO	$(1-3)\cdot 10^{-5}$	"	[73]	
HCl	2.10^{-7}	"	[72]	
HCl	$<10^{-6}$	OAO	[165]	With 1 atm-km CO_2
Hf	$(1-3)\cdot 10^{-9}$	Spectroscopy	[72]	
CH_4	$<10^{-6}$	"	"	
CH_3Cl	$<10^{-6}$	"	"	
CH_3f	$<10^{-6}$	"	"	
C_2H_2	$<10^{-6}$	"	"	
HC_1	$<10^{-6}$	"	"	
O_3	$<10^{-8}$	Spectroscopy	[121]	
O_3	$<3.10^{-9}$	OAO	[165]	With 1 atm-km CO_2
SO_2	$<3.10^{-8}$	Spectroscopy	[78]	
SO_2	$<10^{-8}$	OAO	[165]	With 1 atm-km CO_2
COS	$<10^{-6}$	Spectroscopy	[76]	
COS	$<10^{-8}$	"	[131]	

Table 3 (Continued)

Component	Relative Content	Method of Determination	References	Note
COS	$<10^{-7}$	OAO	[165]	With 1 atm-km CO_2
$C_3)_2$	$<5.10^{-7}$	Spectro-scopy	[79]	
C_3O_2	$<10^{-7}$	OAO	[165]	With 1 atm-km CO_2
H_2S	$<2.10^{-4}$	Sepctro-scopy	[76]	
H_2S	$<10^{-7}$	OAO	[165]	With 1 atm-km CO_2
NH_3	$<3.10^{-8}$	Spectro-scopy	[131]	
NH_3	10^{-4}-10^{-3}	Venera 8	[6]	With P = 2-10 kg/cm^2
NH_3	$<10^{-7}$	OAO	[165]	With 1 tam-km CO_2
NH_3	$<10^{-5}$	Radio Astronomy	[25]	
NO	$<10^{-6}$	OAO	[165]	With 1 atm-km CO_2
NO	$<10^{-6}$	Spectro-scopy	[?]	
NO_2	$<6.10^{-7}$	"	"	"
NO_2	$<10^{-8}$	OAO	[165]	With 1 atm-km CO_2
N_2O_4	$<4.10^{-8}$	"	"	"
HCHO	$<3.10^{-6}$	Spectro-scopy	[?]	
HCHO	$<10^{-6}$	OAO	[165]	With 1 atm-km CO_2
CH_3CHO and higher order alde-hydes	$<10^{-6}$	"	"	"
CH_3COCH_3 and higher order ketones	$<10^{-6}$	"	"	"

TABLE 4

Length of Year on Mars Between Moments of Equinoxes and Soltices in Our Epoch, in Mean Solar Days Universal Time

Northern spring and southern fall	199
Northern summer and southern winter	182
Northern fall and southern spring	146
Northern winter and southern summer	160
Duration of one cycle	687

TABLE 5

CONTENT OF VOLATILES [kg/cm^2) [118, 151]

Volatiles	Atmosphere of Earth	Total on Earth	Atmosphere of Venus	Atmosphere of Mars
CO_2	$3\cdot10^{-4}$	70 ± 30	90 ± 15	$(1.4\pm0.2)\cdot 10^{-2}$
H_2O	$10^{-2}.10^{-3}$	375 ± 75	$10^{-1}-10^{-4}$	$(1.5-2.5)\cdot 10^{-6}$
O_2	0.23	≈0.23	$<10^{-3}$	$<2.5\cdot10^{-5}$
N_2	0.75	≈0.75	<2	$<0.8\cdot10^{-3}$
A_g	10^{-2}	$\approx10^{-2}$	?	$<0.3\cdot10^{-2}$
CO	$10^{-6}-10^{-7}$	$\approx10^{-6}$	$<10^{-3}$	$0.7\cdot10^{-5}$
Cl	--	5.7	$2\cdot10^{-5}$	--
F	--	3.10^{-4}	10^{-7}	--

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NOTES /134

1 The section on Venus was written by M. Ya. Marov, the sections on Mercury and Mars -- by V. D. Davydov.

2 The astronomical unit, equal to the large half axis of the ellipse of the orbit of the Earth, is $149.598 \cdot 10^6$ km; according to the most recent and precise measurements [52], it is equal to the distance traveled by light in the time interval 449.004780± ±0.000001 sec, whereas the speed of light in a vacuum (also a fundamental constant) $c = 299772.4562 \pm 0.0011$ km·sec^{-1} [214].

3 The bond albedo (or spherical albedo) is expressed by a fraction, the numerator of which shows the flux of solar radiation reflected by the daylit hemisphere of a planet in all directions, while the denominator shows the flux of solar radiation striking the planet. To the name of the albedo we add a word indicating either absence of limitations of spectral range (integral albedo), or the type of spectral sensitivity of the radiation receiver used (for example, visual albedo).

4 The name of the system of coordinates on the surface of Mercury comes from the Greek name for this planet -- Hermes.

5 The radar cross section of a planet is found from the total power of reflected radio radiation; it is defined as the geometric cross section of an ideally conducting sphere at the same distance as the planet being studied and yielding the same radio echo power; it is usually expressed as a percent of the geometric cross section of the planet.

6 The term sidereal relates to the movement of the object in the system of coordinates coupled to the fixed stars.

7 The brightness temperature is the temperature of an absolutely black body of the same dimensionsn and same luminance as the body observed in a limited spectral range. The color (or spectrophotometric) temperature is parameter T in the well known formula of Planck, with the value of the parameter selected so as to best approximate the observed distribution of energy of radia- /135
tion of the body in a given wavelength interval.

8 The geostrophic wind is the characteristic horizontal even straight-line movement of air characteristic for altitudes of over 1 km (in the terrestrial atmosphere), for which the pressur gradient is balanced by the Coriolis force, while the force of friction is negligible. The wind is directed along an isobar, and its velocity $U = (1/2\omega\rho \cdot \sin \phi\Delta)(\Delta P/\Delta n)$, where ω is the angular velocity of rotation of the planet, ρ is the density of the gasses, ϕ is the latitude of the point, ΔP is the pressure

difference, Δn is the distance between corresponding isobars.

[9] A graben is a trench limited by faults.

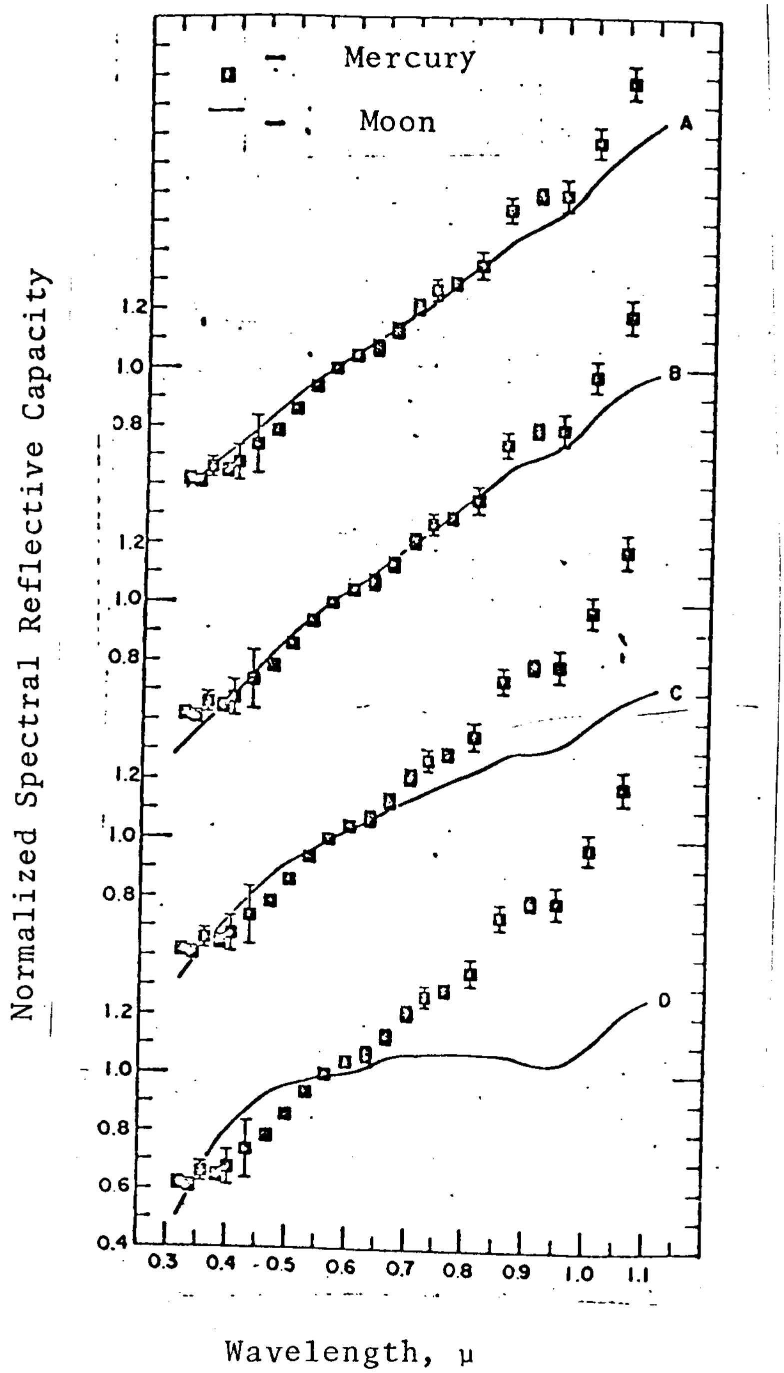


Figure 1. Spectral Reflective Capacity of Mercury and its Comparison with Reflection Spectra of Various Territories of the Moon: (a) Mountains; (b) "Sea"; (c) Bright Craters in Mountain Areas; (d) Bright Crater (from McCord and Adams [143])

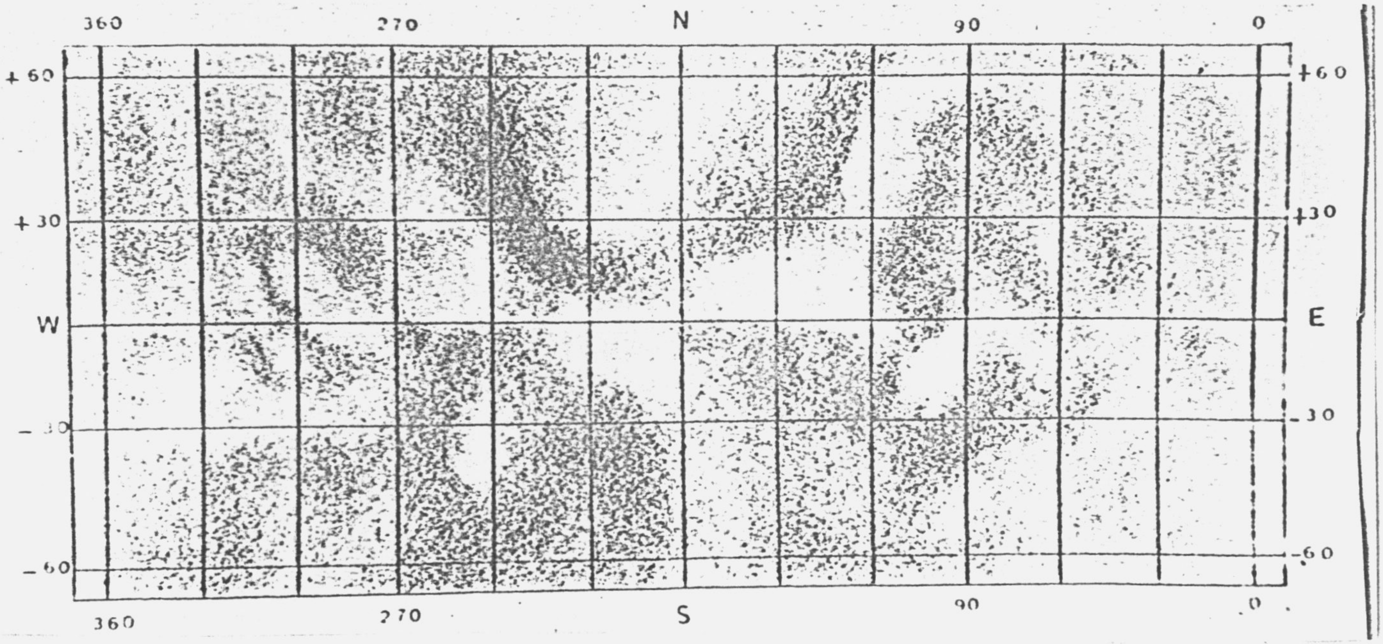


Figure 2. Map of the Surface of Mercury, After [162]

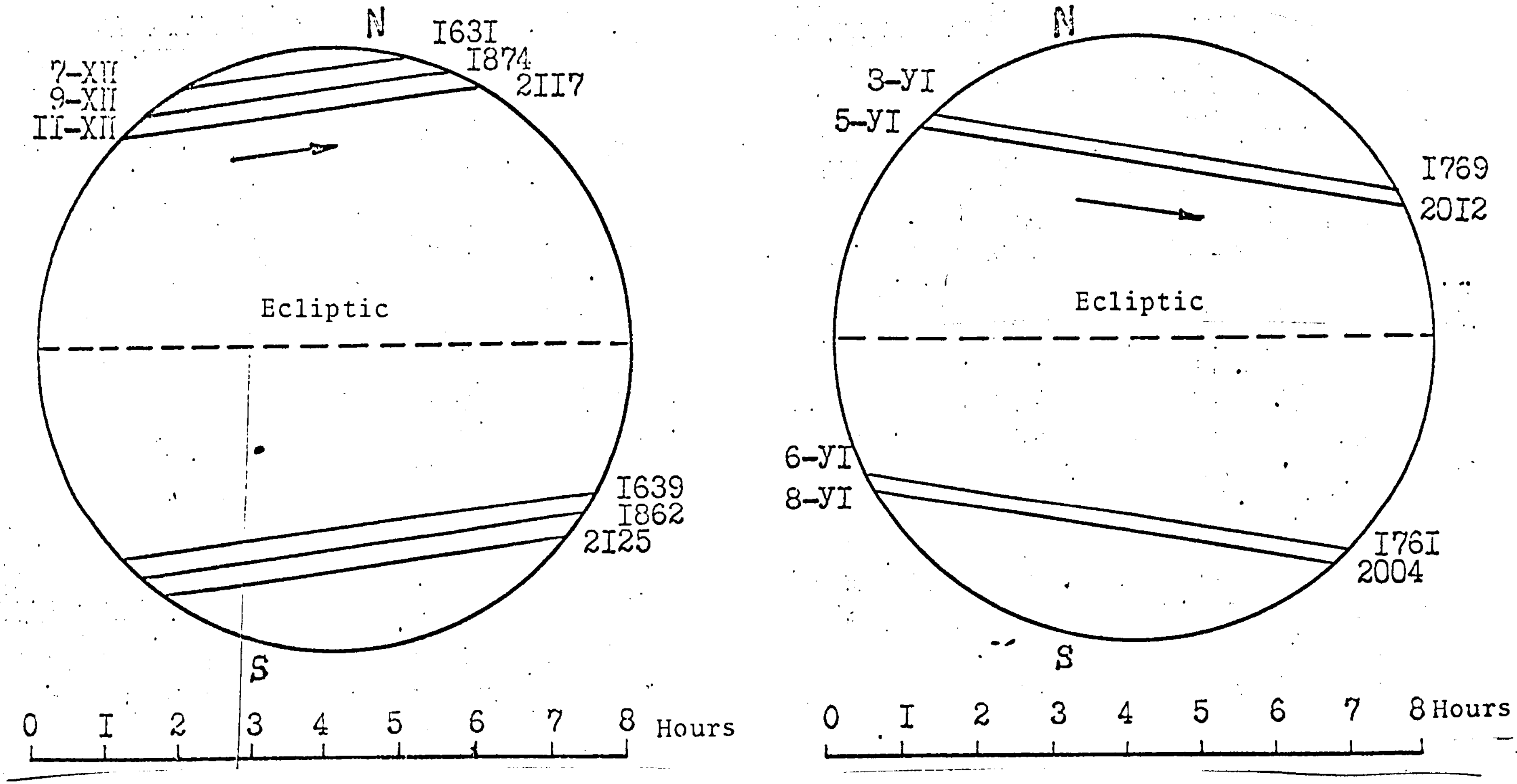


Figure 3. Moments of Passage of Venus over the Disc of the Sun

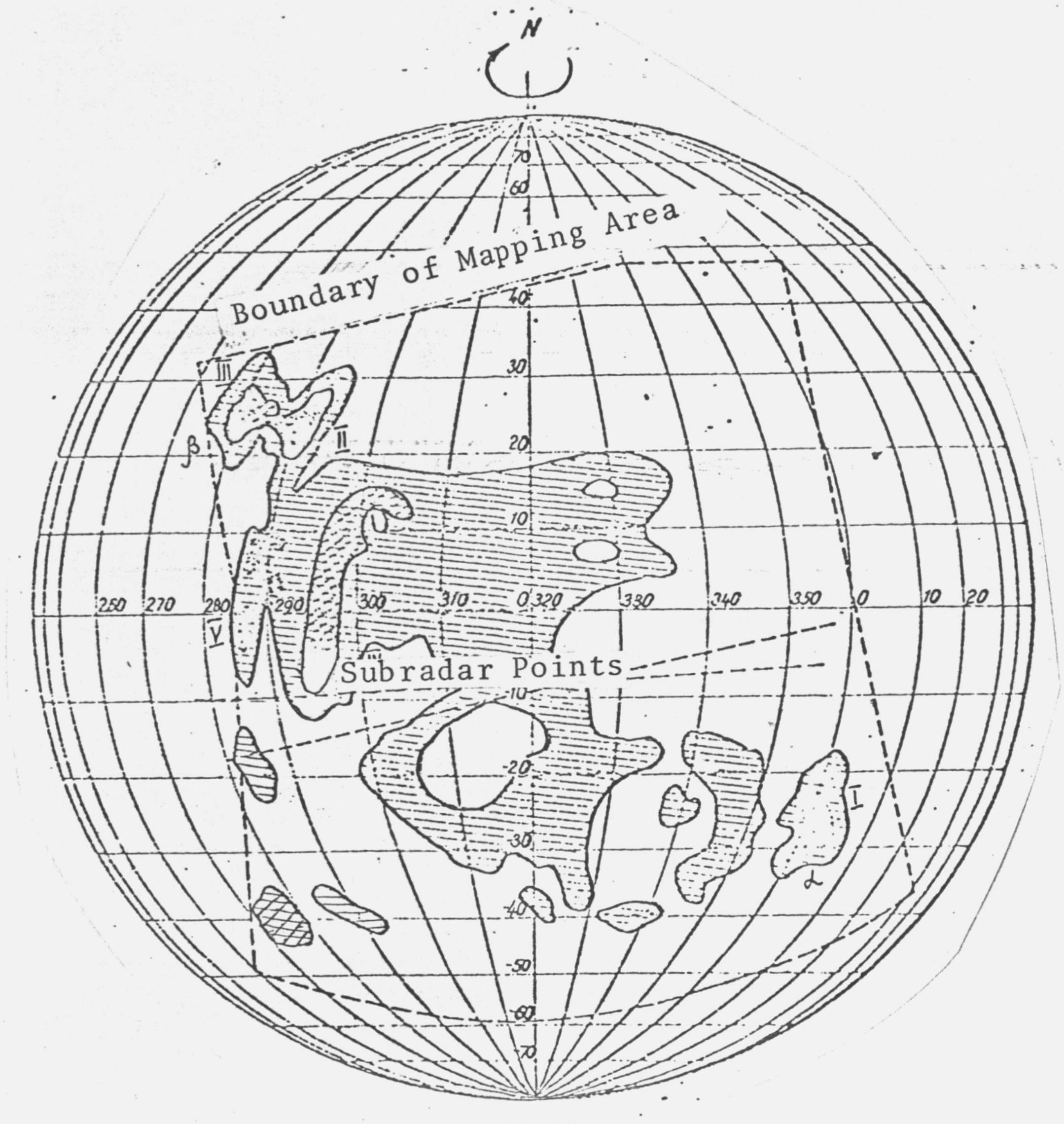


Figure 4. Map of Reflective Properties of the Surface of Venus

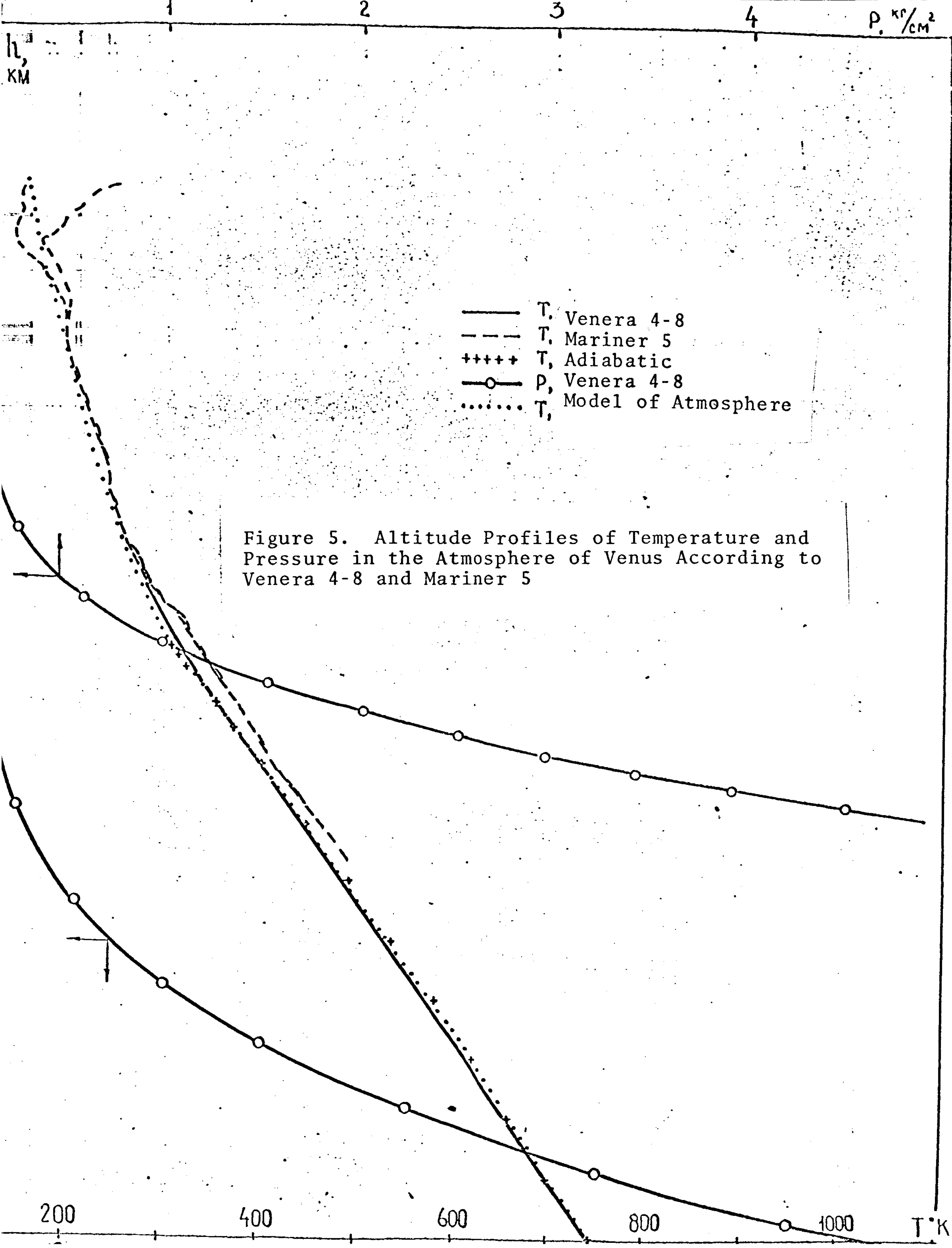


Figure 5. Altitude Profiles of Temperature and Pressure in the Atmosphere of Venus According to Venera 4-8 and Mariner 5

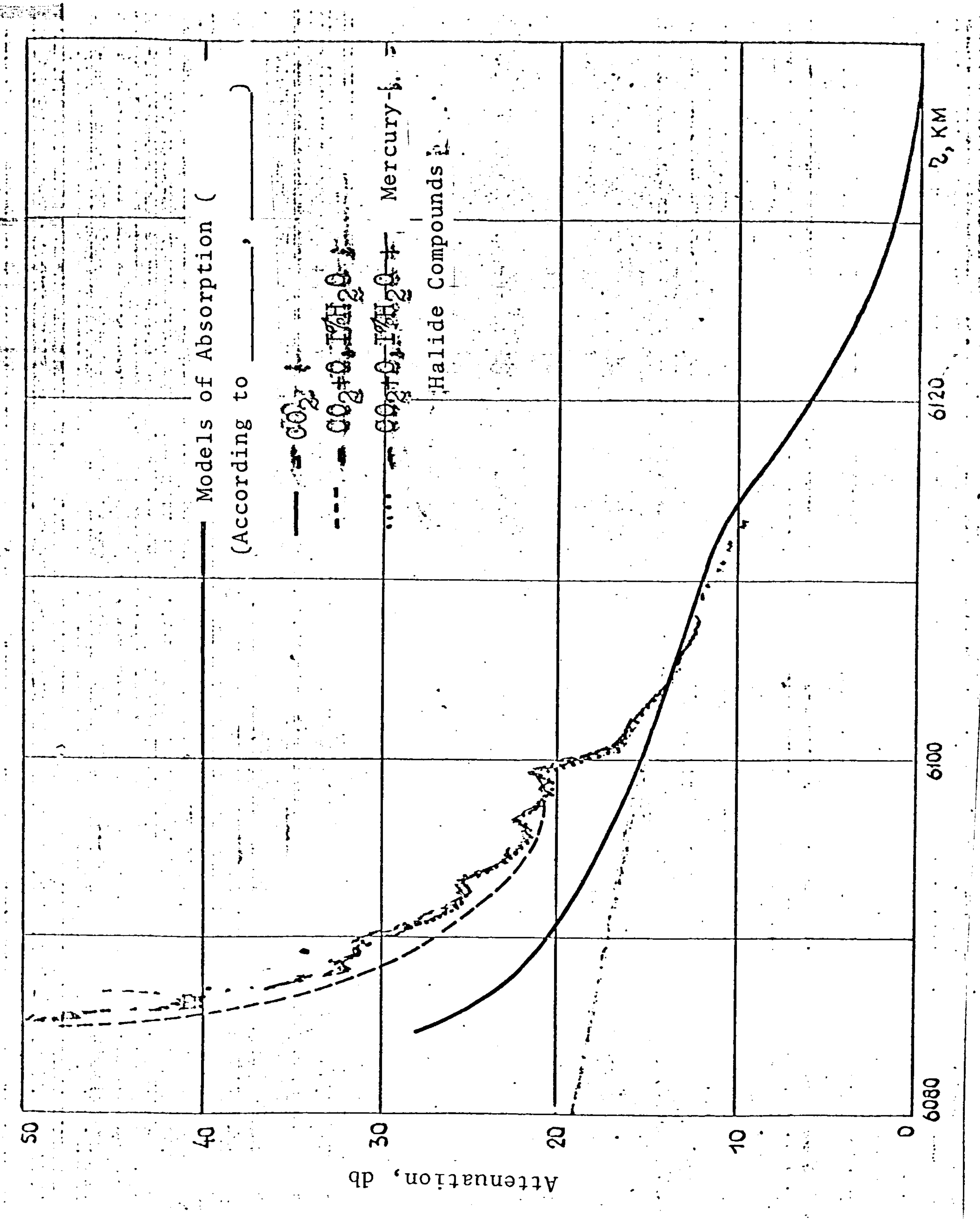


Figure 6. Nature of Attenuation of Radio Signals in the Atmosphere of Venus and Approximateing Models

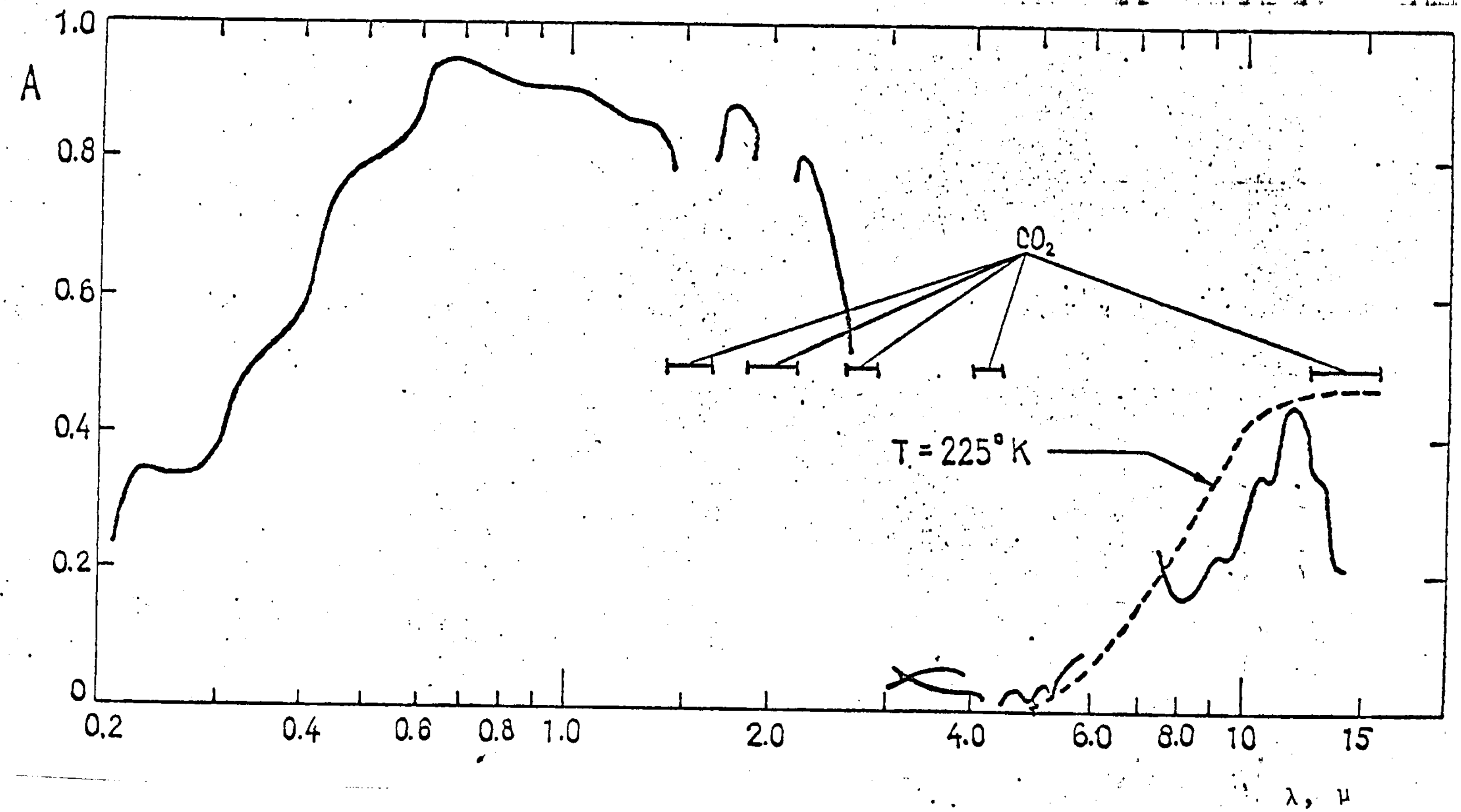


Figure 7. Basic Reflective and Emission Characteristics of Venus

Figure 8. Phase Diagram of H_2O with Estimates of Levels of Condensation and Extent of Clouds with Concentrations of H_2O 1% and 0.1% for Various Atmospheric Models

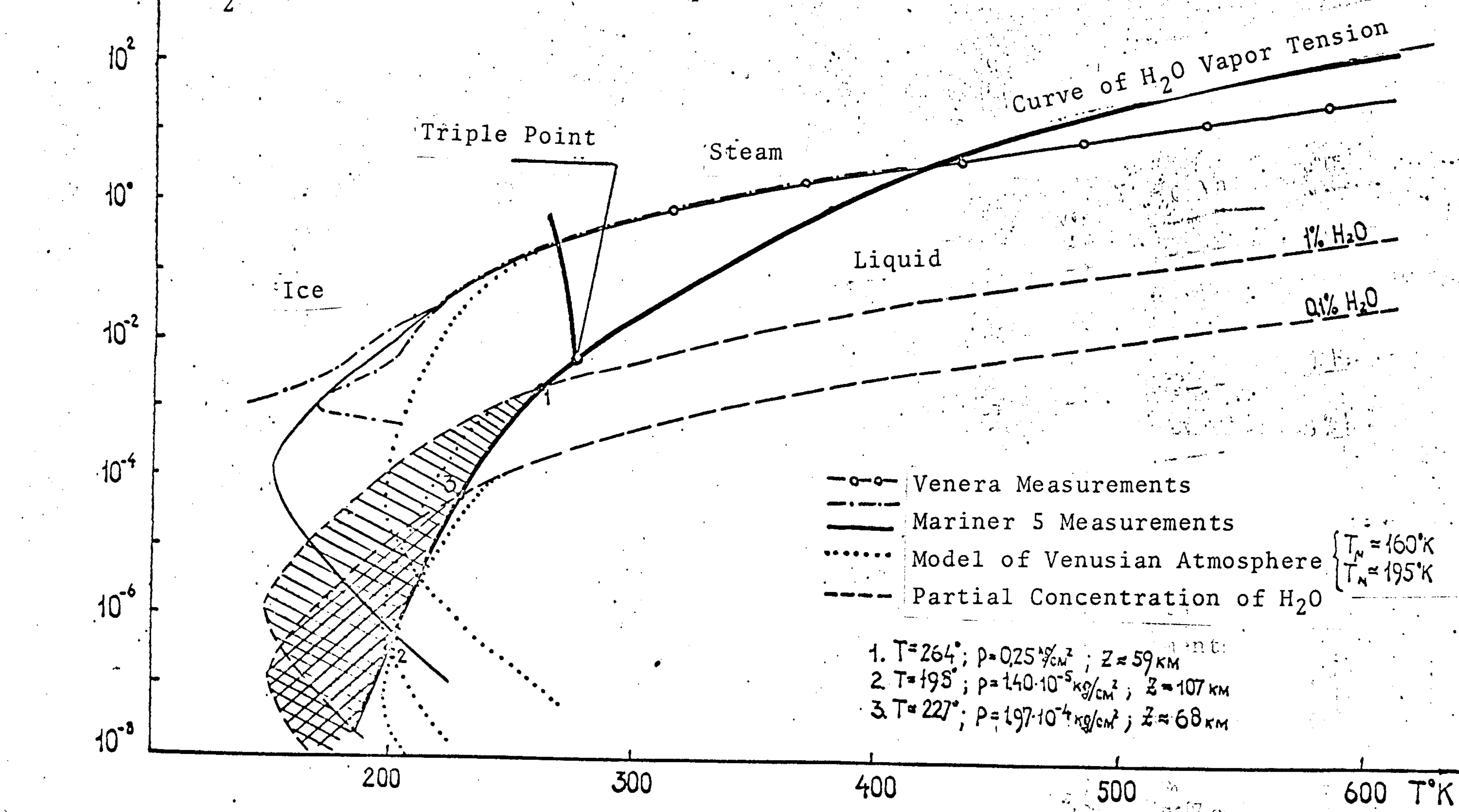


РИС. 8

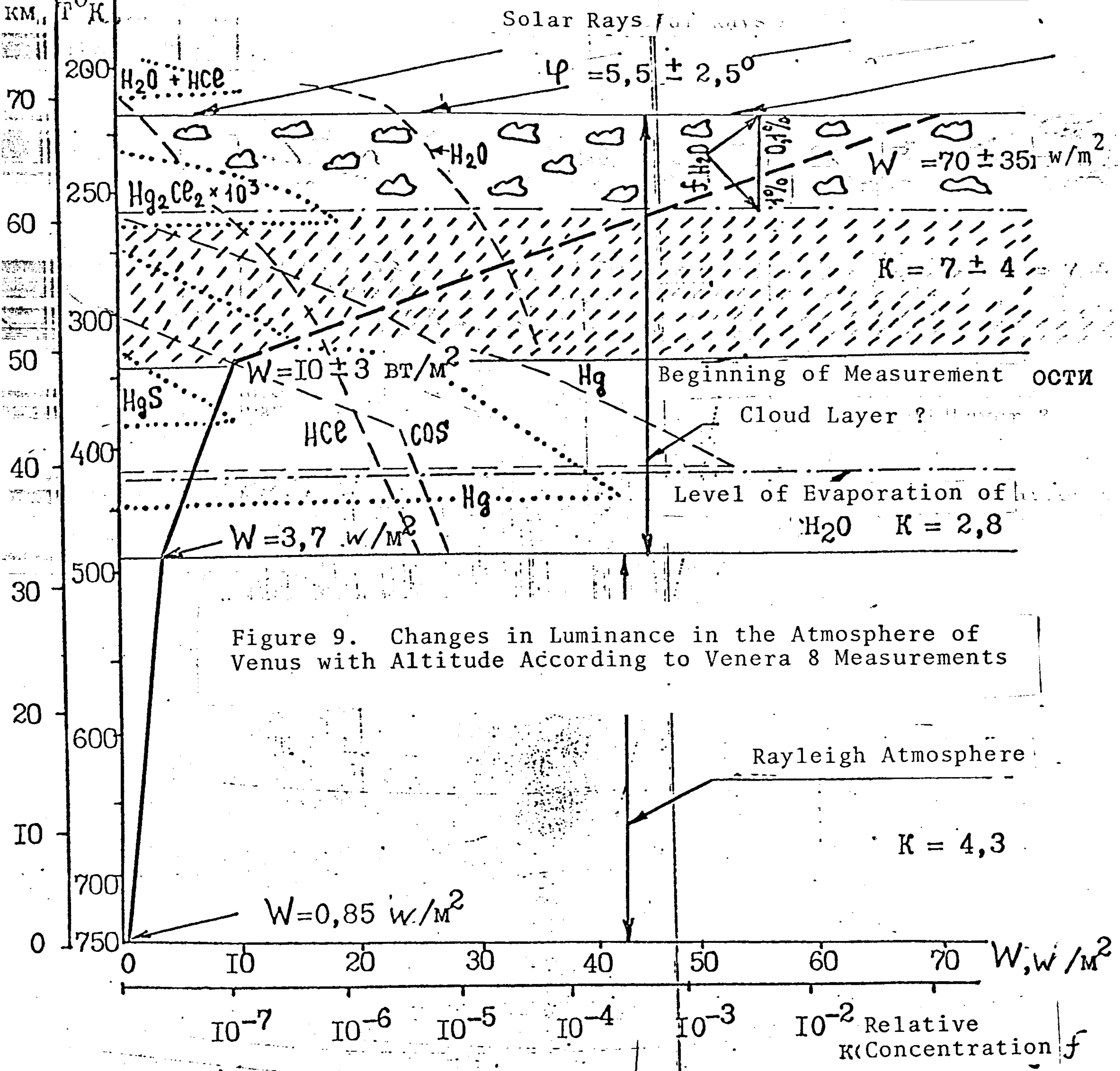


Figure 9. Changes in Luminance in the Atmosphere of Venus with Altitude According to Venera 8 Measurements

K – Index of Attenuation

Luminance (for Spectral Composition of Radiation Corresponding to Solar Radiation)

S (Lux) = 350 W (BT/M²)

..... Clouds } According to Geochemical Model of Lewis

——— Gasses } (Where $f_{H_2O} \simeq 10^{-5}$-10^{-4})

Area of Hypothetical Clouds of H_2O with Relative Content $f_{H_2O} \simeq 1\%$; where $f_{H_2O} \simeq 0.1\%$, Level of Condensation Coincides with Arbitrary Upper Boundary of Clouds)

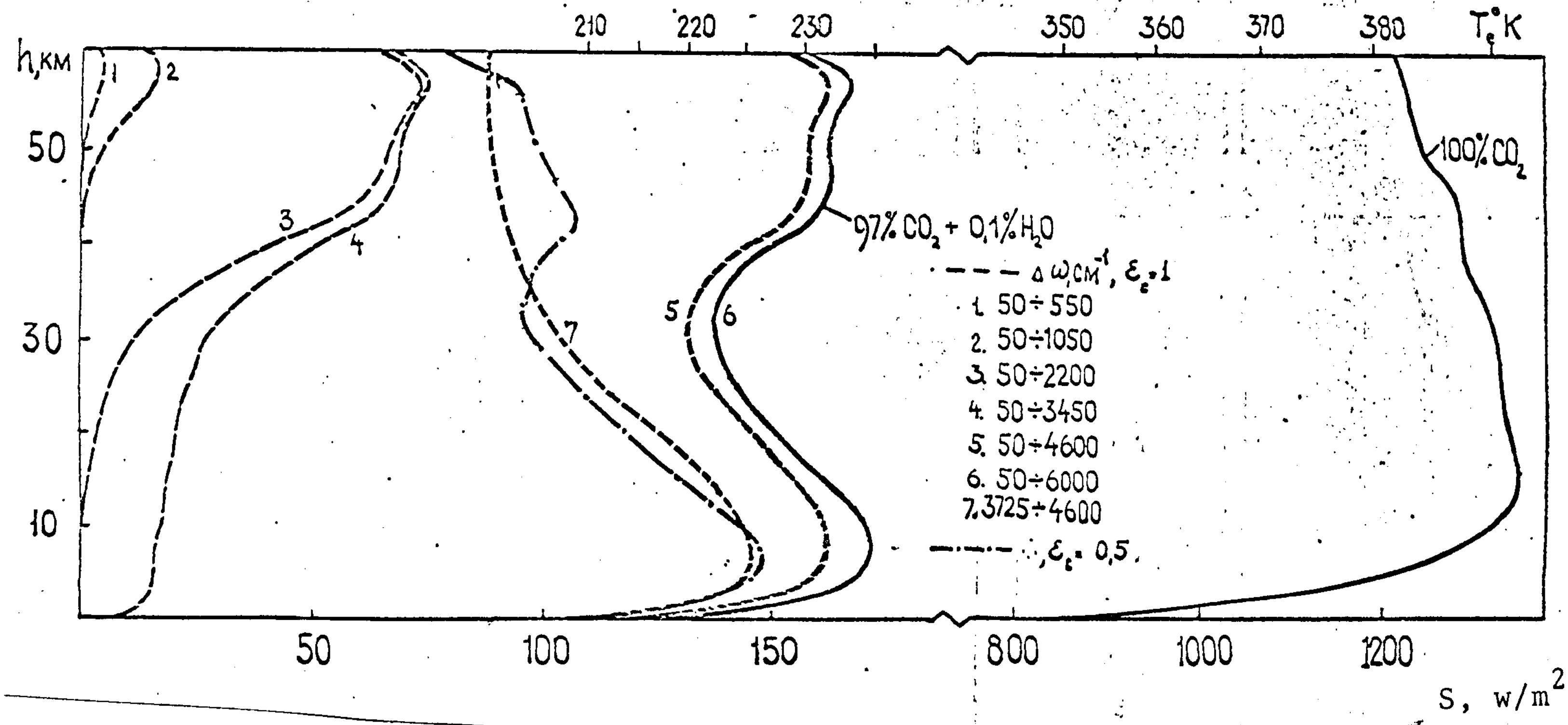


Figure 10. Profiles of Radiation Fluxes of Departing (Summary) Radiation Under Various Conditions

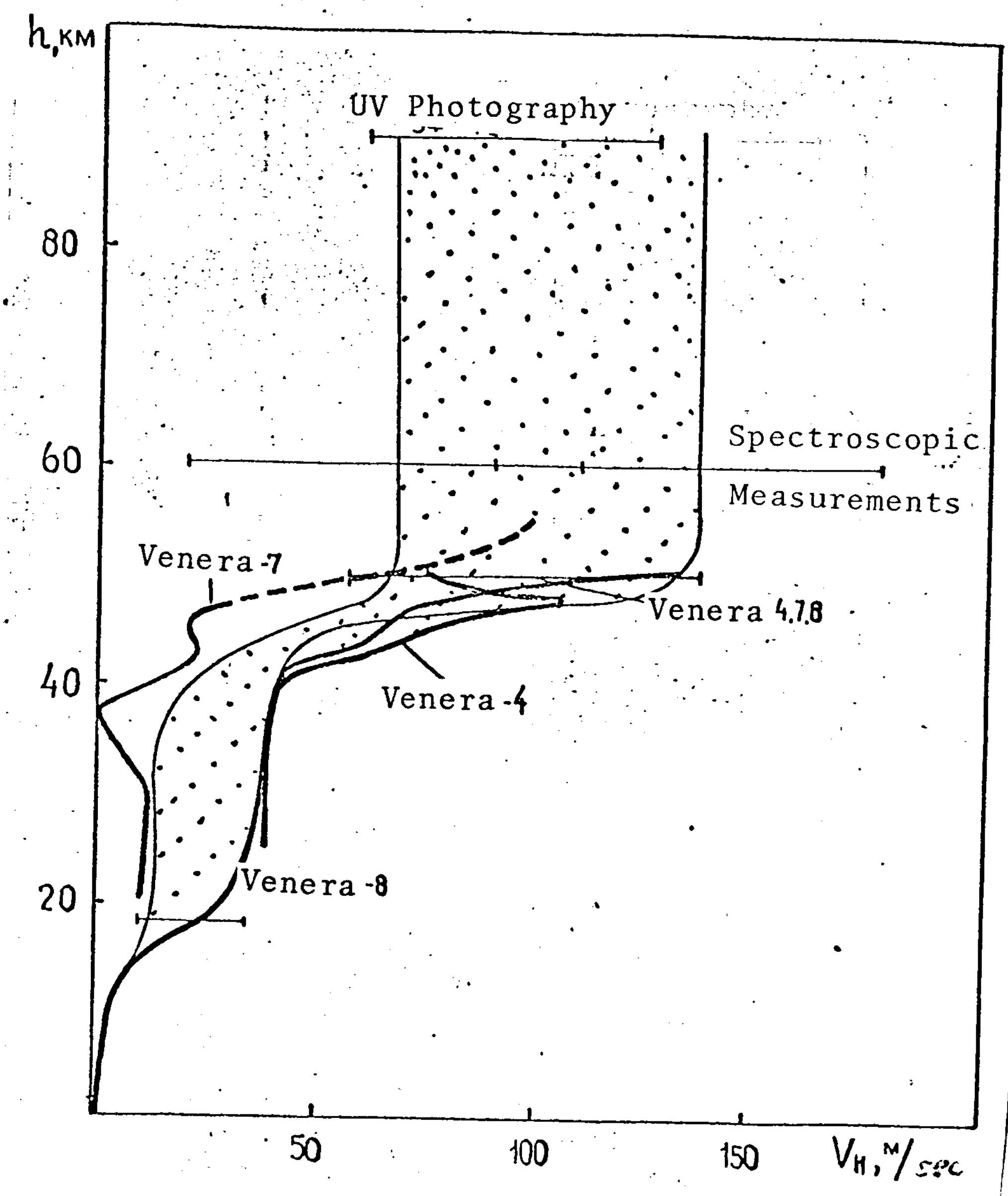


Figure 11. Velocities of Horizontal Movements in the Atmosphere of Venus According to Measurements of Venera 4, 7 and 8

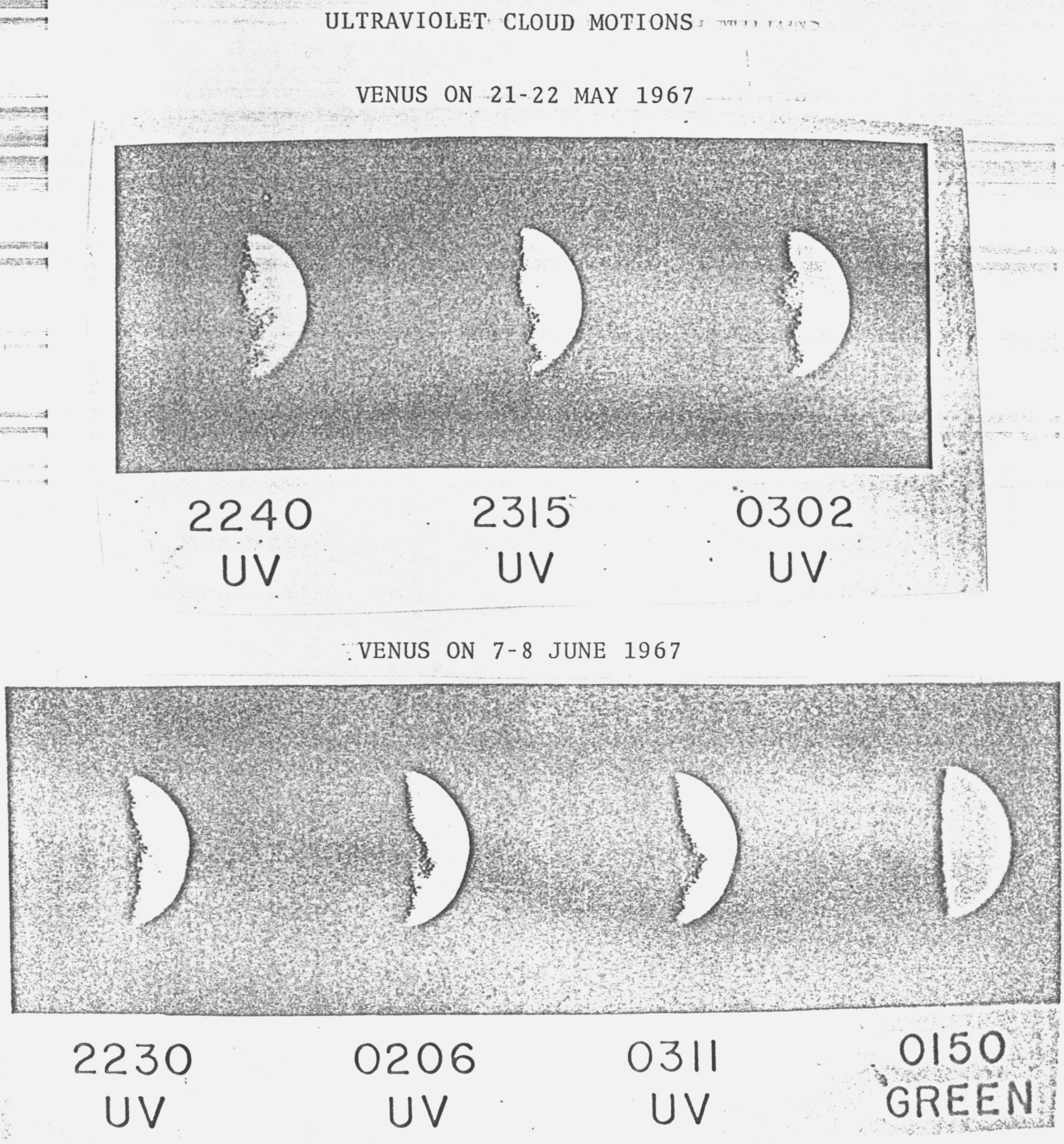


Figure 12. Photograph of Venus in UV Rays (According to [201])

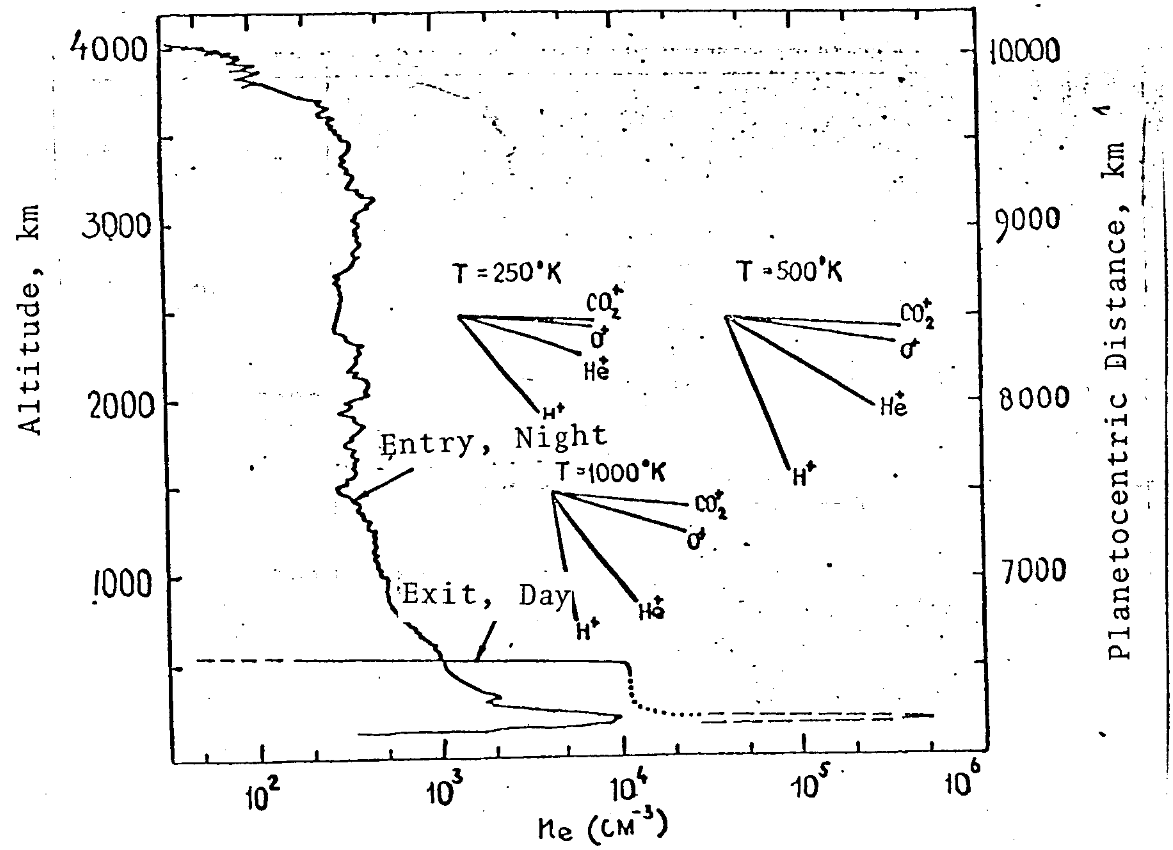


Figure 13. Change in Electron Concentration with Altitude on Night and Day Sides According to Measurements of Mariner 5 with Estimates of Corresponding Values of Scale of Altitudes (According to [150])

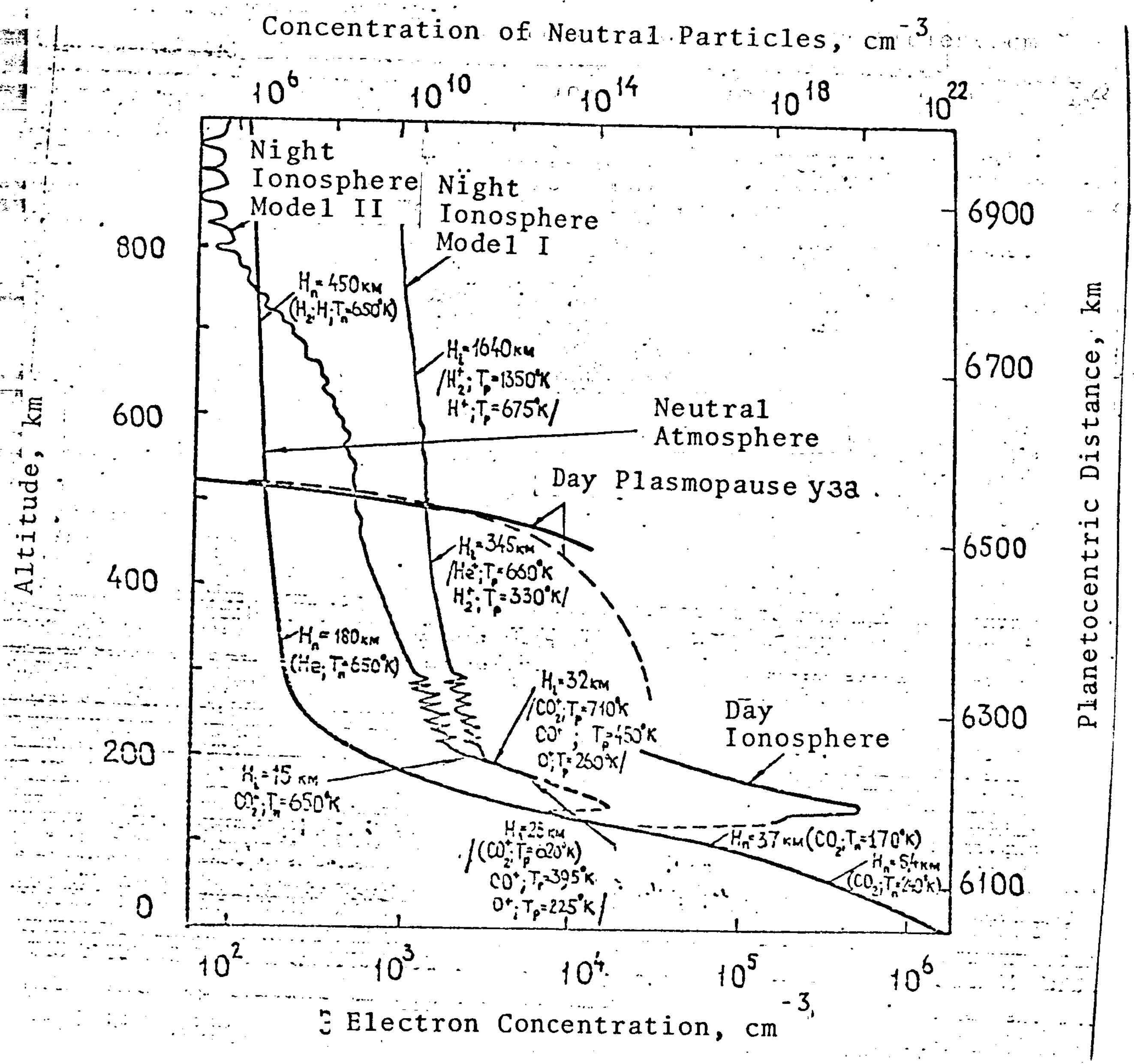

Concentration of Neutral Particles, cm^{-3}
10^6 10^{10} 10^{14} 10^{18} 10^{22}
Night Ionosphere Model II
Night Ionosphere Model I
H_n = 450 km (H_2; H; T_n = 650°K)
H_i = 1640 km / H_2^+; T_p = 1350°K H^+; T_p = 675°K /
Neutral Atmosphere
Day Plasmopause узл
H_i = 345 km / He^+; T_p = 660°K H_2^+; T_p = 330°K /
H_n = 180 km (He; T_n = 650°K)
H_i = 32 km / CO_2^+; T_p = 710°K CO^+; T_p = 450°K O^+; T_p = 260°K /
Day Ionosphere
H_i = 15 km CO_2^+; T_n = 650°K
H_i = 25 km / (CO_2^+; T_p = 620°K) CO^+; T_p = 395°K O^+; T_p = 225°K /
H_n = 37 km (CO_2; T_n = 170°K)
H_n = 54 km (CO_2; T_n = 240°K)
Altitude, km
800
600
400
200
0
Planetocentric Distance, km
6900
6700
6500
6300
6100
10^2 10^3 10^4 10^5 10^6
Electron Concentration, cm^{-3}

Figure 13a

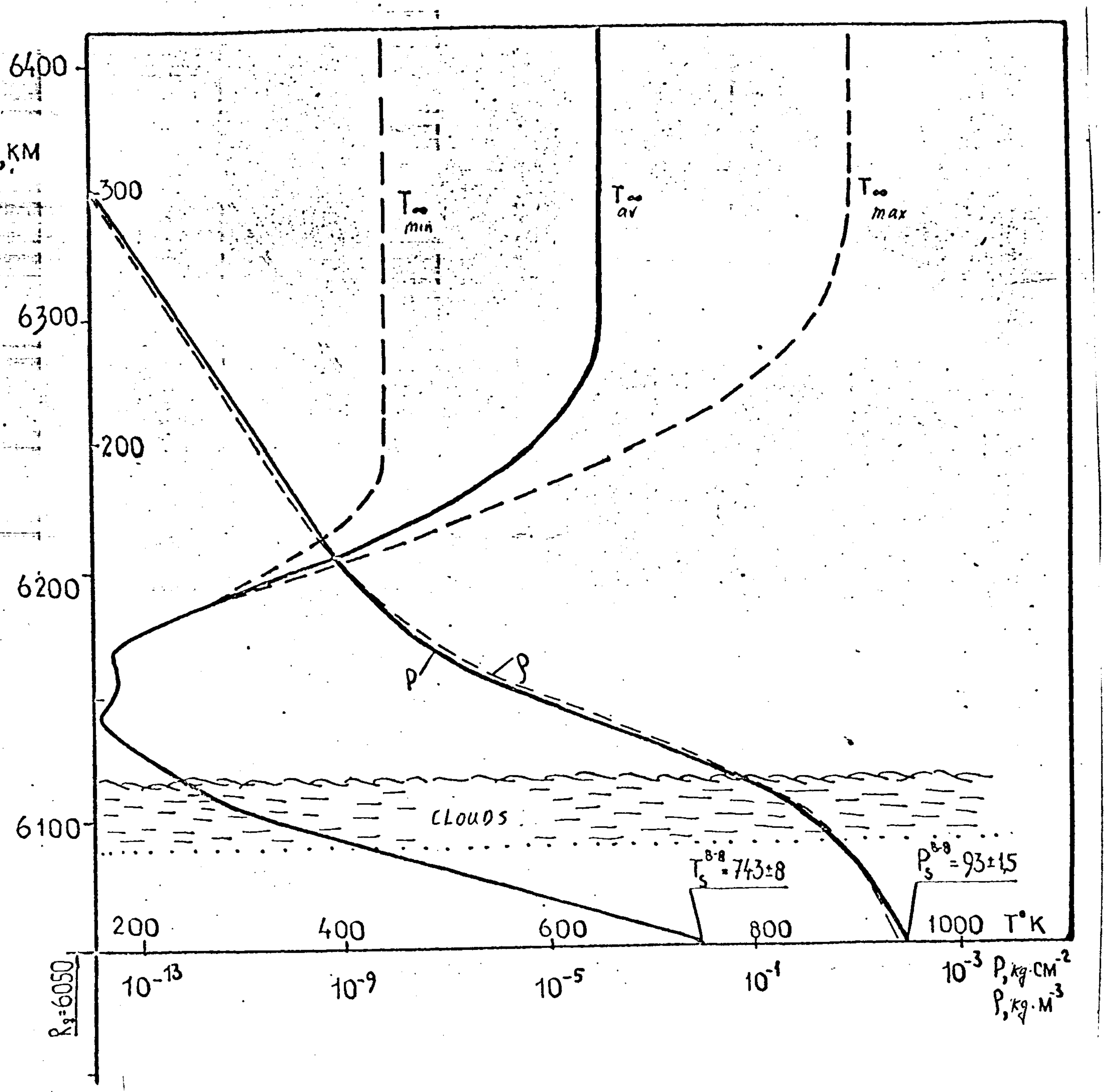


Figure 14. Physical Structure of the Atmosphere of Venus According to Model of [36]

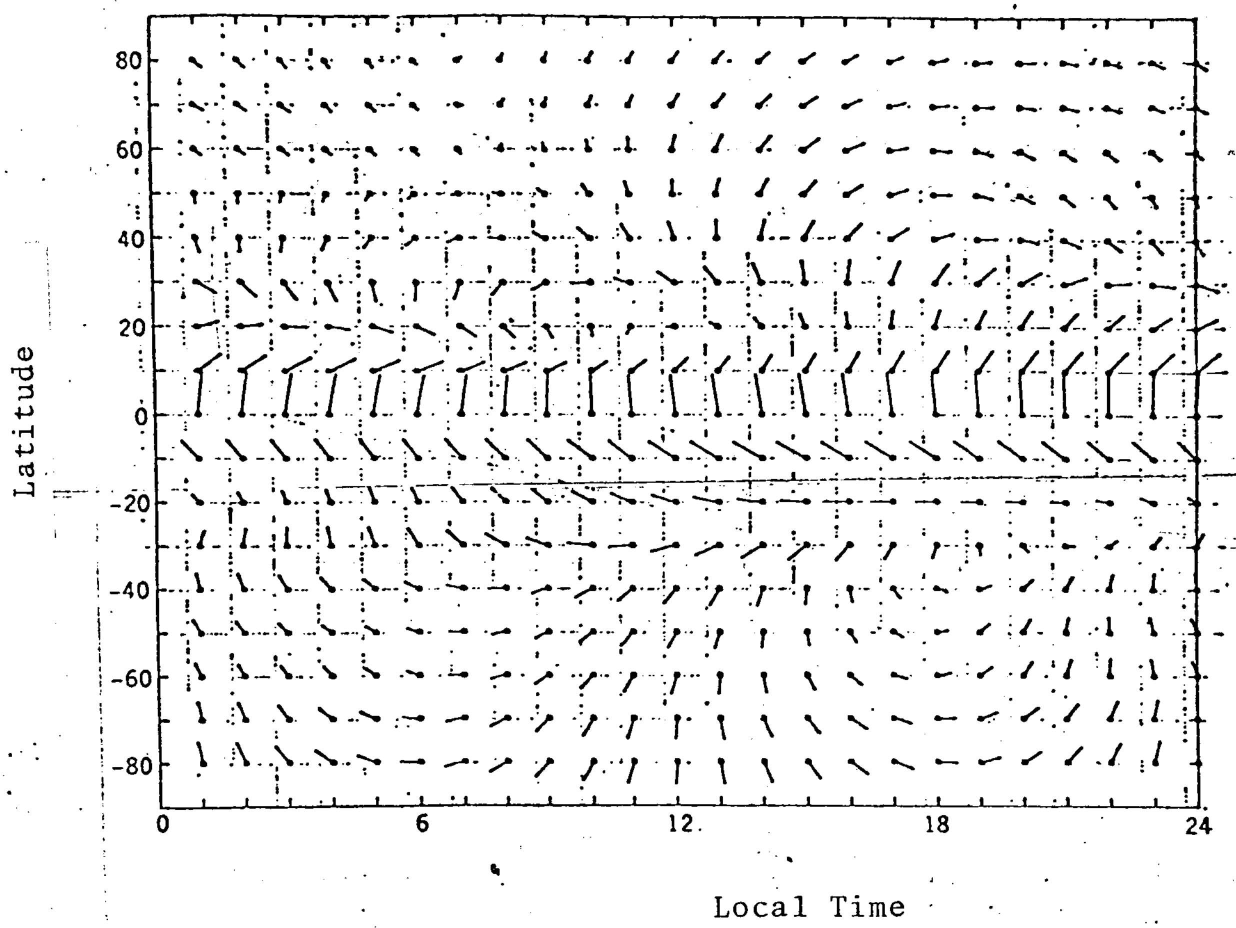


Figure 15. Field of Martian Winds at 2.2 mb Atmospheric Pressure Level During Global Dust Storm, Calculated [107] on the Basis of Temperature Model of the Atmosphere. Initial Assumptions: Hydrostatic Equillibrium; Smoothness of Mars; Constant Pressure at Base of Atmosphere. Direction and Speed of Wind Shown by Vectors Departing from Points. Length of Vector Equal to Distance Between two Neighboring Points Corresponding to Windspeed of 50 m/sec

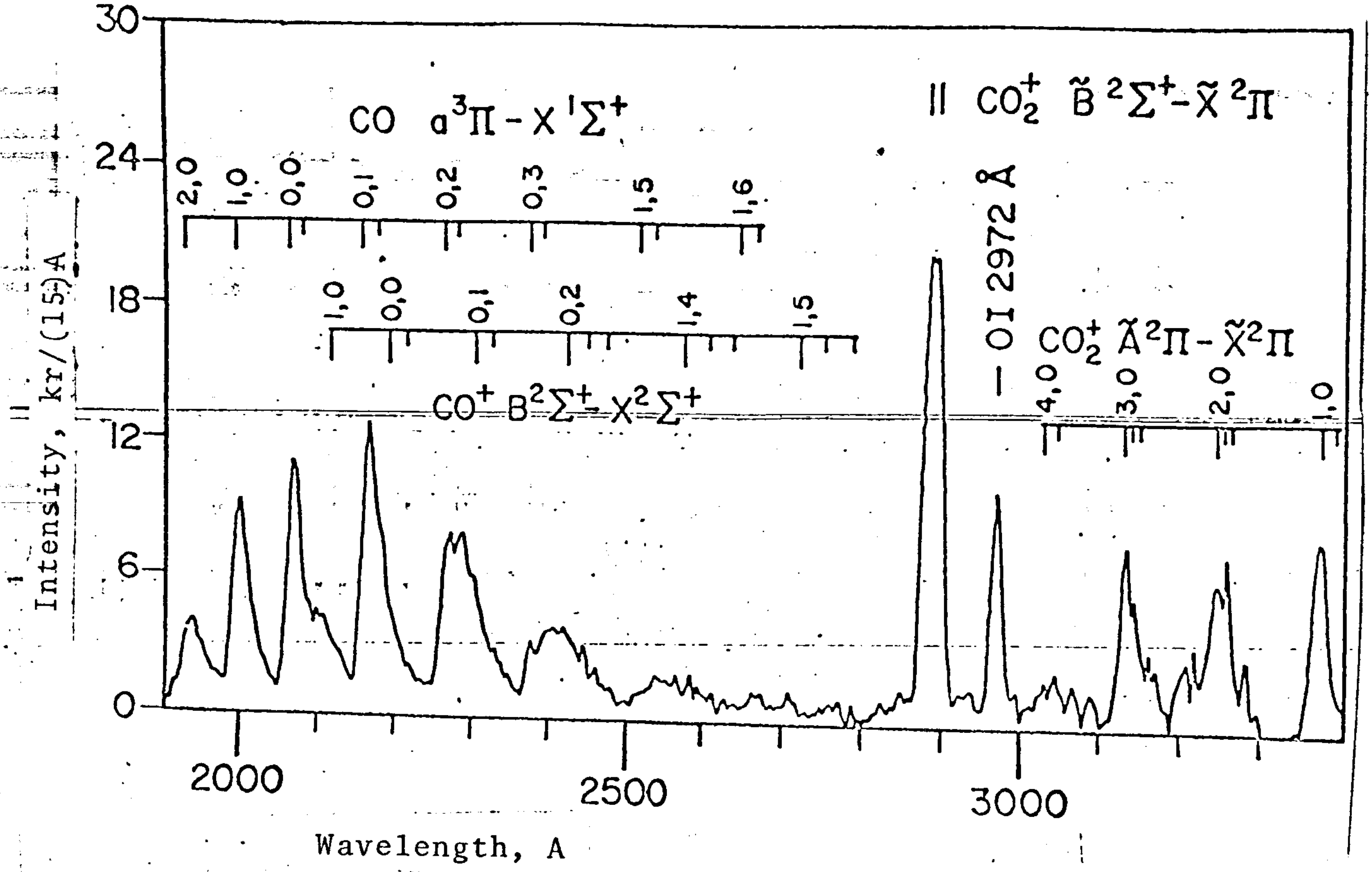


Figure 16. Ultraviolet Spectrum of Day Glow of Atmosphere of Mars, Average of 120 Recordings of Mariner 9 in November-December 1971. Cameron Bands of CO, First Negative System of Bands of CO^+, Intensive Doublet and Band of CO_2^+ and Line of Neutral Atomic Oxygen Identified

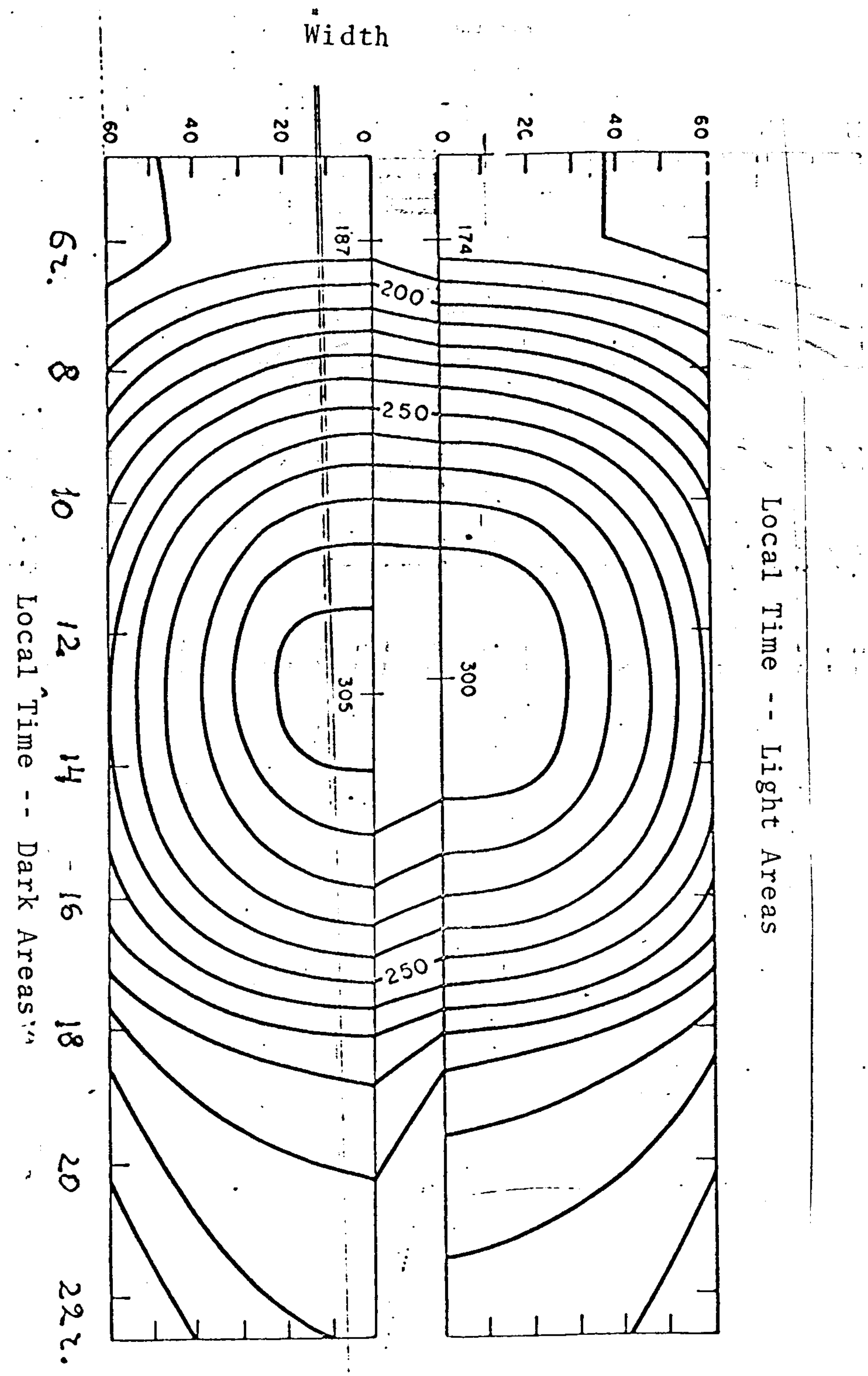


Figure 17. Latitude Distribution of Temperature in Light and Dark Areas of the Surface of Mars as a Function of Local Time (During Season of Equinox, Spring in Southern Hemisphere) Determined by Morrison, Sagan and Pollak [159] by Processing of Radiometric Observations of Sinton and Strong

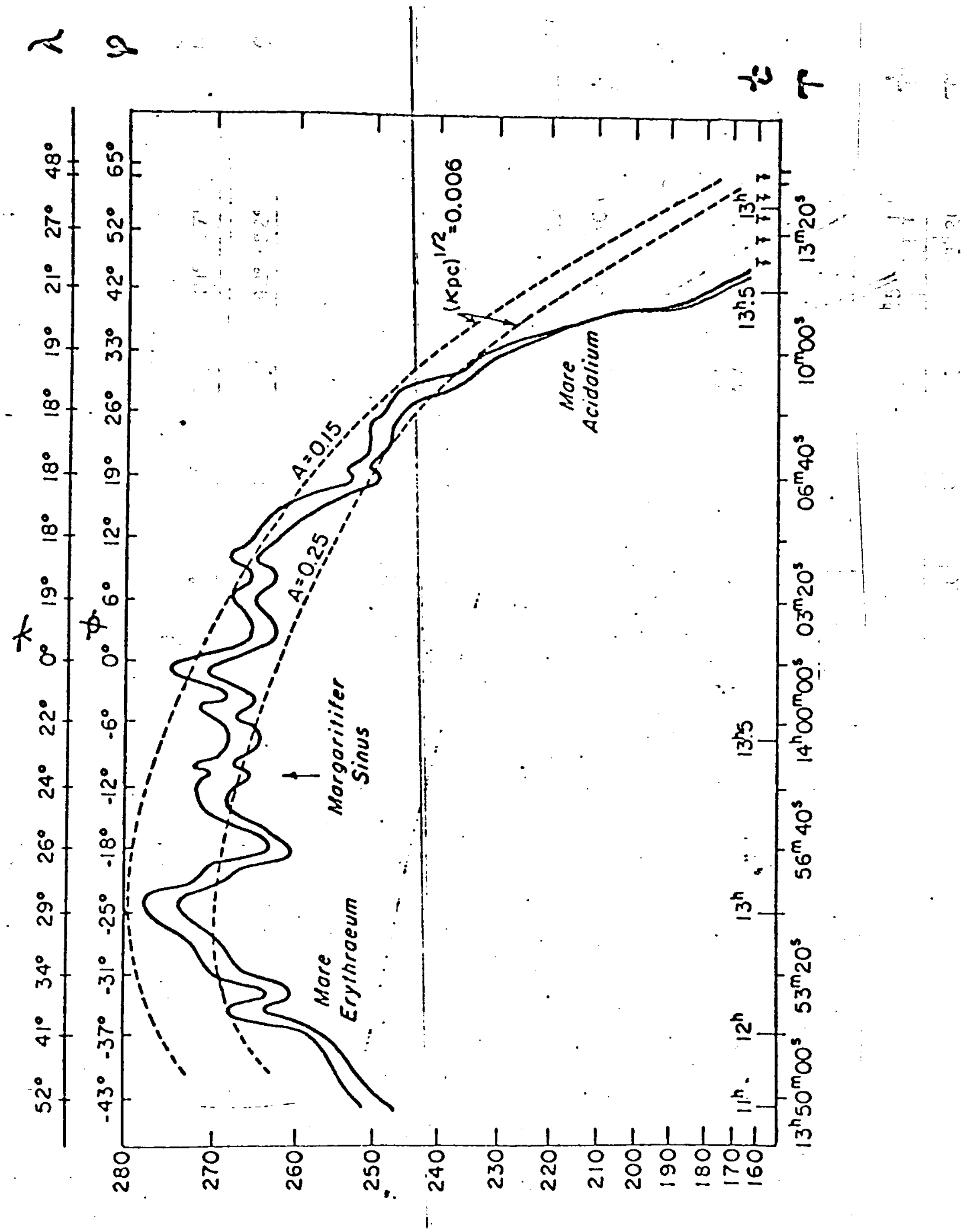


Figure 18. Infrared Brightness Temperature from Observations of Mars 3 (42 A) of 28 February 1972 in °K. Ordinate: Scale Linear For Energetic Flux of Planck Radiation. Horizontal Scales Show: γ -- Latitude and λ -- Longitude of Point on Ray of Vision of Instrument, t -- Local Solar Time on Mars, T -- Moscow Statutory Time of Observation. Graphs Show: Measured Temperature by Two Solid Curves Differing as to Correction for Absorption in the Atmosphere; Dotted Curves Note Theoretical Brightness Temperature for "Seas" (Upper) and "Continents" (Lower) for $(k\rho s)^{1/2} = 0.006$ cal$\cdot$cm$^{-2}\cdot$sec$^{-1/2}\cdot$°K^{-1}

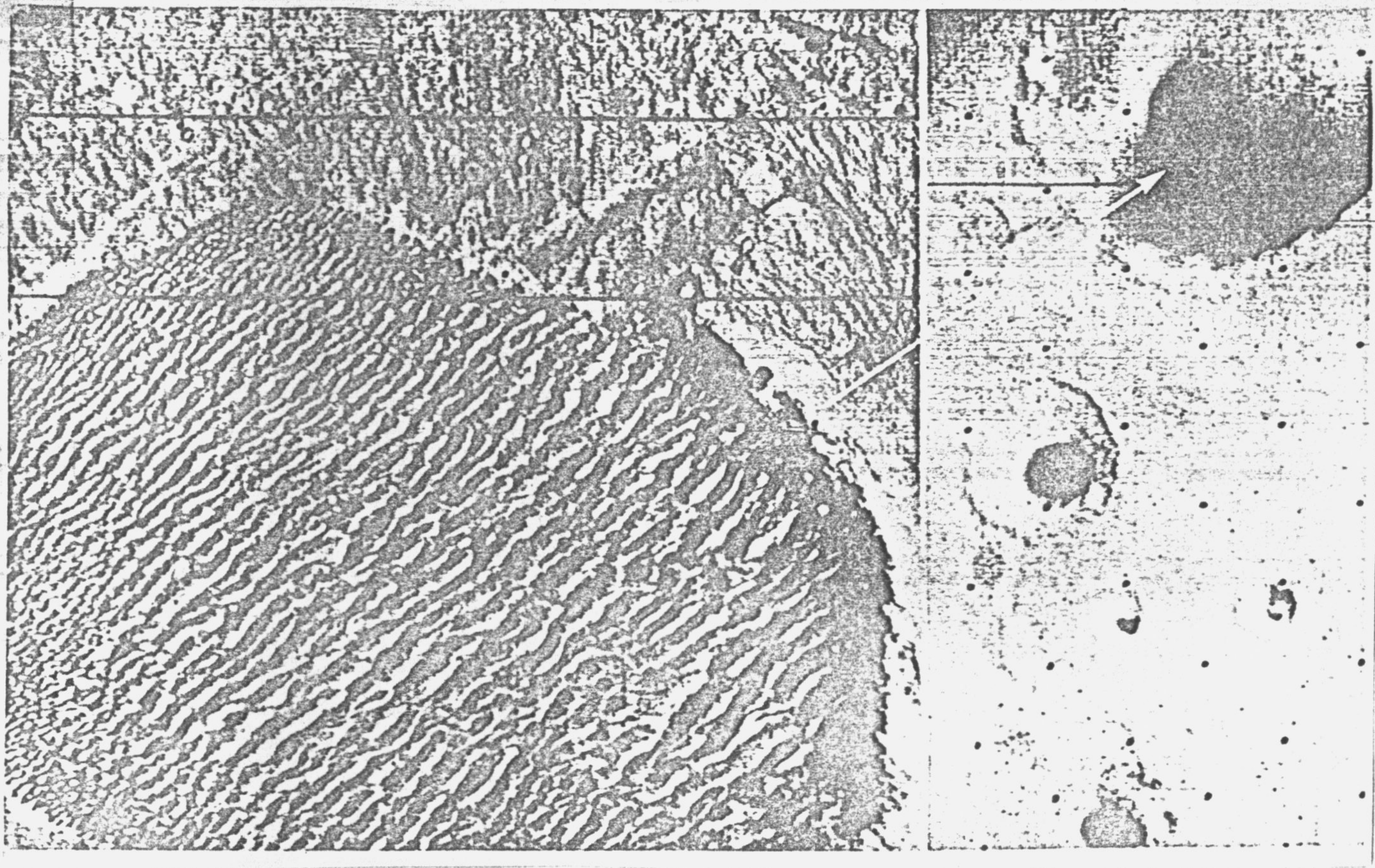


Figure 19. Section of Bottom of 150-Kilometer Crater in Region of Hellespontus in Zero-Angle Camera of Mariner 9 on Photograph of Surface Covered with Dunes Taken by Wide-Angle Camera Appears as Very Dark Spot

Figure 20. Martian Volcano Nix Olympica, 500 km in Diameter at Base. Edge of Volcanic Shield Separated from Adjacent Plane by Steep Cliffs. Main Crater 65 km in Diameter Located at over 10 km Altitude with Several Volcanic Apertures. Mariner 9 Picture

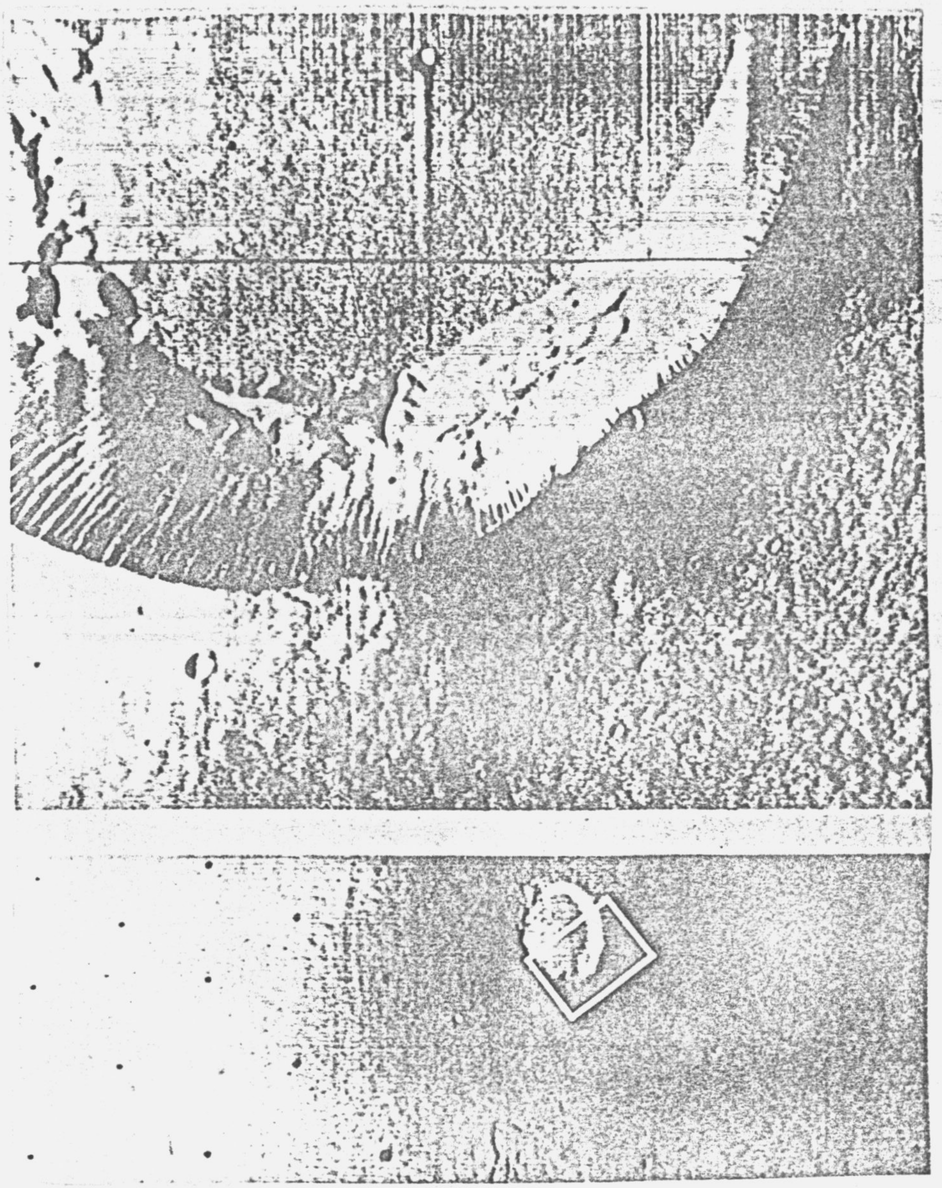


Figure 21. Portion of Rim and Floor of 40 km Crater atop Highest Martian Peak in Center of Dark Volcanic Shield Called Middle Spot. Mariner 9 Photograph

Figure 22. Portion of Martian Grand Canyon. Mariner 9 Photograph

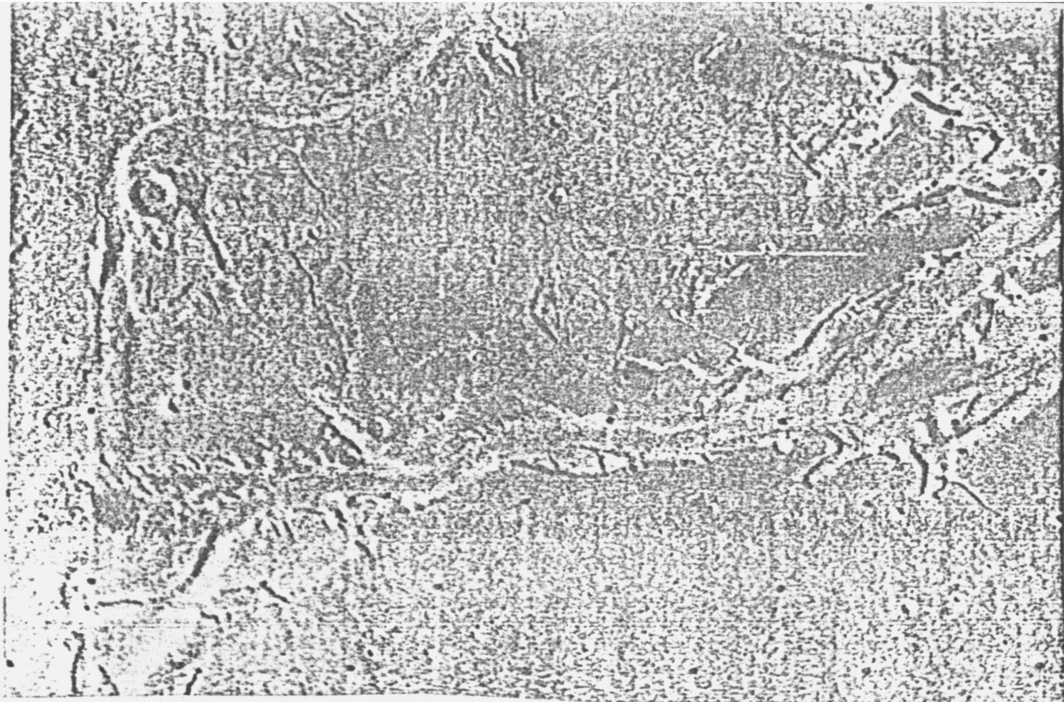
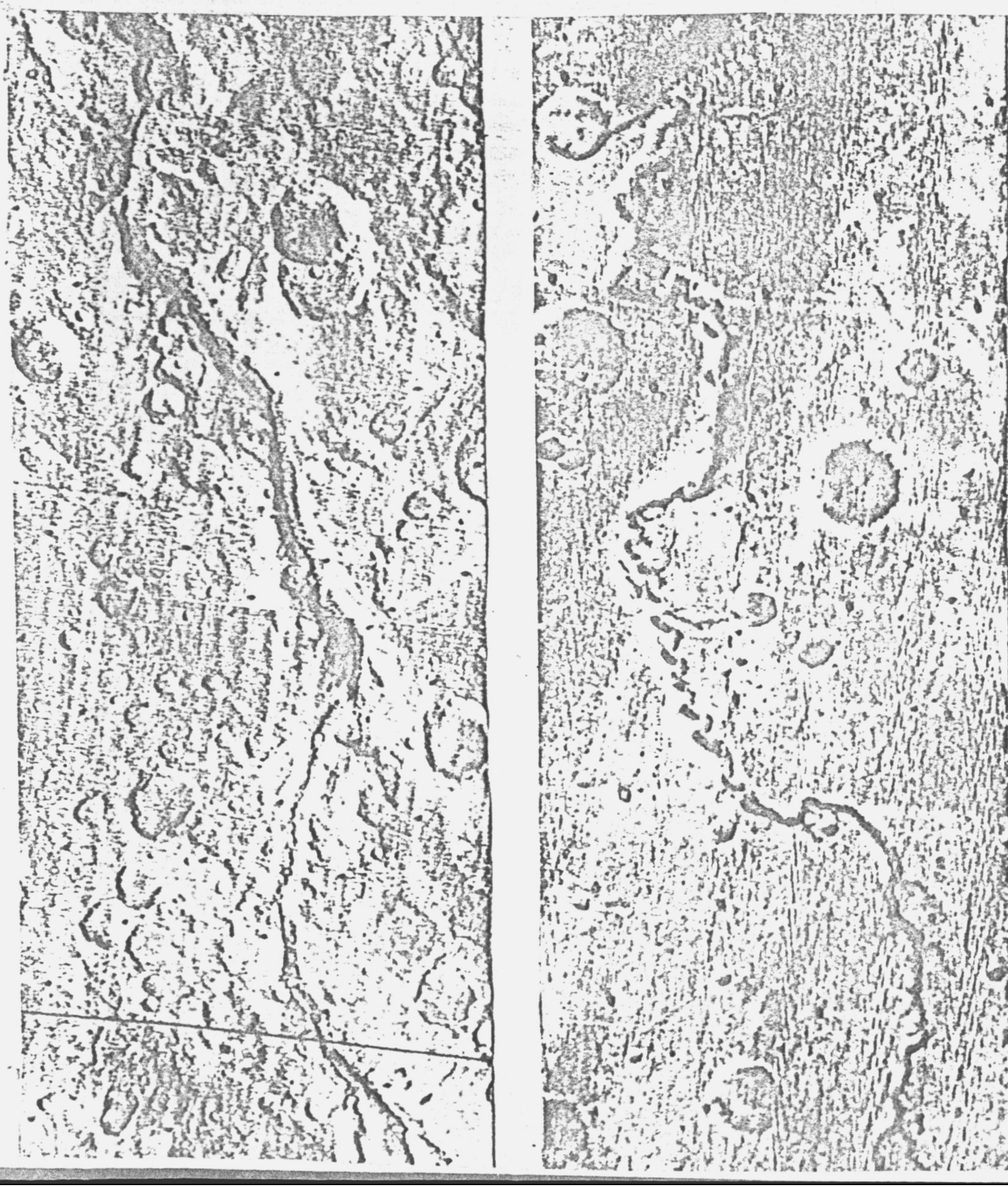


Figure 23. Examples of Large Stream-Like Formations on Mars, Mariner 9 Photographs



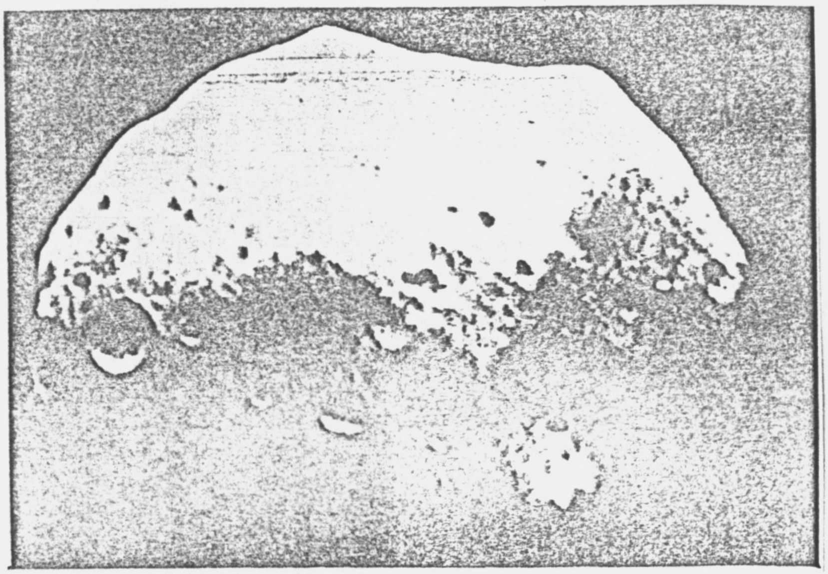


Figure 24. The Martian Satellite Phobos.
Telephoto Taken by Mariner 9.

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16. Abstract This review presents the results of Soviet and American studies of three planets -- Mercury, Venus and Mars. Information produced since the dawn of the space age is emphasized. Unfortunately, the limited volume of the chapter makes it impossible to include data on the best studied of the Earth-type planets, the Earth itself.

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